No. 98-830

In The Supreme Court of the United States

October Term, 1998

Amoco Production Company, on behalf of itself and the class it represents,*

Petitioners,

v.

Southern Ute Indian Tribe,

and

Bruce Babbitt, Secretary of the United States Department of Interior, *et al.*,

Respondents.

On Writ of Certiorari to the United States Court of Appeals for the Tenth Circuit

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JOINT APPENDIX
VOLUME II

Carter G. Phillips **
Stephen B. Kinnaird
Sidley & Austin
1722 Eye Street, N.W.
Washington, D.C. 20006
(202) 736-8000

Charles L. Kaiser
Anthony J. Shaheen
Davis, Graham & Stubbs LLP
Suite 4700
370 Seventeenth Street
Denver, CO 80202
(303) 892-9400

Counsel for Petitioner Amoco Production Company (class representative)

Thomas H. Shipps **
Frank E. Maynes
Maynes, Bradford, Shipps & Sheftel, LLP
P.O. Box 2717
Durango, CO 81302
(970) 247-1755

Counsel for Respondent Southern Ute Indian Tribe

Seth P. Waxman **
Solicitor General
Department of Justice
Washington, D.C. 20530
(202) 514-2217

Counsel for Federal Respondents

(Additional Counsel Listed on Inside Cover)

* Named class members listed in Addendum A of Petitioners' Brief.

** Counsel of Record.

PETITION FOR CERTIORARI FILED: NOVEMBER 18, 1998
CERTIORARI GRANTED: JANUARY 22, 1999
ORDER GRANTING CERTIORARI AMENDED: JANUARY 29, 1999

GARY L. PAULSON
REBECCA S. MCGEE
DAVID E. BRODY
AMOCO CORPORATION
1670 Broadway
Denver, CO 80201
(303) 830-4040
Counsel for Petitioner
Amoco Production Company
(class representative)

G. R. MILLER
MCDANIEL, BATY &
MILLER, LLC
1040 Main Avenue
P.O. Box 1157
Durango, CO 81302
(970) 247-1113
Counsel for Certain
Named Class Members

SCOTT B. MCELROY
ALICE E. WALKER
GREENE, MEYER &
MCELROY, P.C.
1007 Pearl Street
Suite 220
Boulder, CO 80302
(303) 442-2021

MICHAEL T. MCCONNELL
LONG & JAUDON
1600 Ogden Street
Denver, CO 80218-1414
(303) 832-1122
Counsel for Respondent
Southern Ute Indian Tribe

TABLE OF CONTENTS

VOLUME I — Page

District Court Docket Entries 1

Court of Appeals Docket Entries 133

First Amended Complaint 158

Matthew J. Mavor Affidavit and Report 184

Douglas M. Smith Affidavit and Report 234

Dan Yee Affidavit and Report 259

Documents Regarding the John J. Patterson Entry 278

Stephen L. Bend Affidavit 298

James T. Cooper Affidavit 322

J. Craig Creel Affidavit 328

Jeffrey R. Levine Affidavit 342

Harry Marsh Affidavit 370

John H. Simpson Letter to the Honorable Thomas M. Carter 399

VOLUME II

Marius R. Campbell, *Contributions to Economic Geology, 1906, Part II—Coal, Lignite, and Peat*, U.S.G.S. Bulletin 316, H.R. Doc. No. 823, 59th Cong., 2d Sess. (1907) 401

Rollin T. Chamberlin, *Notes on Explosive Mine Gases and Dust*, U.S.G.S. Bulletin 383, H.R. Doc. No. 1538, 60th Cong., 2d Sess. (1909) 415

Papers on the Conservation of Mineral Resources, U.S.G.S. Bulletin 394, H.R. Doc. No. 1554, 60th Cong., 2d Sess. (1909) 473

Cassius A. Fisher, *Depth and Minimum Thickness of Beds as Limiting Factors in Valuation reprinted in The Valuation of Public Coal Lands*, U.S.G.S. Bulletin 424, H.R. Doc. No. 502, 61st Cong., 2d Sess. (1910) 505

TABLE OF CONTENTS—Continued

Page

Horace C. Porter and F.K. Ovitz, *The Escape of Gas From Coal*, U.S. Bureau of Mines Technical Paper 2 (1911) 508

Robert H. Fernald, *The Status of the Gas Producer and of the Internal-Combustion Engine in the Utilization of Fuels*, U.S. Bureau of Mines Technical Paper 9 (1912) 524

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Harry Perry, *The Gasification of Coal*, 230 *Scientific American*, No. 3 (Mar. 1974) 530

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Jeffrey R. Levine, *Coal Composition, as Related to the Mode of Occurrence of "Coalbed Methane"* (1992) 579

NOTICE

The following documents have been omitted in the printing of this Joint Appendix. They are reproduced in the Appendix to the Petition For A Writ Of Certiorari on the pages indicated below:

Page

A. Opinion of the Court of Appeals (*En Banc*) 1a

B. Opinion of the Court of Appeals (Panel) 52a

C. District Court Opinion 95a

D. Statutes, 30 U.S.C. §§ 81, 83-85 ..... 133a

TABLE OF CONTENTS—Continued

Page

E. *Classification and Valuation of Coal Lands*, 37 Pub. Lands Dec. 653 (1909) 137a

F. *Ownership of And Right to Extract Coalbed Gas in Federal Coal Deposits*, 88 Interior Dec. 538 (1981) 140a

G. *Rights to Coalbed Methane Under an Oil & Gas Lease for Lands in the Jicarilla Apache Reservation*, 98 Interior Dec. 59 (1990) 160a

H. Department of Interior, Department Manual 209 DM 178a

I. Map of Major U.S. Coalbed Methane Resources.. 181a

The following additional documents have also been omitted in the printing of this Joint Appendix. They are reproduced in the Appendix to the Respondent Southern Ute Indian Tribe's Brief In Opposition on the pages indicated below:

Act of March 3, 1909, 35 Stat. 844 ("1909 Act").. 1a

Act of June 22, 1910, 36 Stat. 583 ("1910 Act").... 3a

Pub. L. No. 105-367 ("Enzi Act") 6a

Bureau of Mines, Bulletin 65 (1913) (cover page).. 9a

Bureau of Mines, Bulletin 65, Plate I (map)..... 10a

59TH CONGRESS
2d Session

DOCUMENT
No. 823

HOUSE OF REPRESENTATIVES

Bulletin No. 316

Series—A. Economic Geology, 98
B. Chemistry and Physics, 51

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

CONTRIBUTIONS

TO

ECONOMIC GEOLOGY

1906

Part II.—COAL, LIGNITE, AND PEAT

MARIUS R. CAMPBELL
Geologist in Charge

WASHINGTON
GOVERNMENT PRINTING OFFICE
1907

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CONTRIBUTIONS TO ECONOMIC GEOLOGY, 1906, PART II.

COAL, LIGNITE, AND PEAT.

MARIUS R. CAMPBELL, *Geologist in Charge.*

INTRODUCTION.

By MARIUS R. CAMPBELL.

NEED OF INVESTIGATION.

The constantly growing consumption of coal in the United States has led to the opening of mines in almost every State in the Union and it has also stimulated prospecting to a marked degree. This condition of affairs has created a strong demand for information concerning the extent of the coal fields, the geologic relation of the beds, and the quality of the coal. In the comparatively unknown coal fields of the West the demand is for general information regarding the extent, number, and thickness of the beds and the quality of the coal. In the better known fields the demand is for detailed information which will enable the prospective operator to know how much of any one coal bed is available, and how it lies, so that he may locate his mine in the best position for economic work.

In order to meet this growing demand the Geological Survey has been giving more and more attention to the subject of coal, both as regards its geologic relations and its technology. The need for information in both branches is imperative, for, although the amount of coal in the various fields seems so great as to be well nigh inexhaustible, the consumption is increasing so rapidly that already the question of a future supply of fuel is a serious one and the Government is surely justified in using every means possible to conserve the supply for the use of future generations. Accordingly the technologic branch of the Survey is engaged in studying the fuel problems in order to devise, if possible, less wasteful methods of mining and more economical methods of utilizing the coal after it is mined.

Our chief fuels are coal, oil, and wood. Wood already is almost a thing of the past; oil, although used extensively in some parts of the country for the production of power, is necessarily of limited occurence and before long may cease to be an important factor in the problem. Coal, therefore, is the fuel of the present, and, so far as can be seen, will continue to lead in this particular for a long time to come.

The importance of the coal industry at the present time is well illustrated by a comparison of the values of the leading mineral products of the United States for the year 1905.

Values of six of the leading mineral products of the United States in 1905.[a]

Coal	$476,756,963
Iron	382,430,000
Clay products	149,687,188
Copper	139,795,716
Oil and gas	125,720,254
Gold and silver	122,402,683

[a] Mineral Resources U.S. for 1905, U.S. Geol. Survey, 1906.

So far as fuels are concerned the work of the Geological Survey may be divided into three classes—geologic, technologic, and statistical, the last of which is in charge of the division of mineral resources. The object of this report is to give, in a brief way, a synopsis of the results accompanied in the various branches of the work during the last year in advance of the more detailed reports covering the same subjects.

GEOLOGIC WORK.

All geologic work on the mineral fuels of the United States is under the general supervision of the writer. The work is of various grades and degrees of precision, depending on the needs of the public and the condition under which the surveys are carried on.

In that part of the country west of the 100th meridian the coal fields are comparatively unknown, and the work of the Survey is largely exploratory. Rapid reconnaissance surveys are made over large areas to determine the limits of the field and to obtain such information regarding the number and character of the coal beds and their attitude as may be possible in the present undeveloped condition of the field and with the hasty method of examination. Where the outlines of the fields are already fairly well known the work is largely devoted to a more or less detailed investigation of the number and thickness of the coal beds, the quality of the coal, and the best locations for economical development of the field.

In the eastern fields information is needed almost as badly as in the West, but the work is of a much more detailed character and involves not only a thorough study of the geologic conditions under which the coal occurs, but also a study of the quality of the coal and its adaptability to various commercial uses.

The reports here presented cover results obtained wholly or in part during 1906. Geologic work has been done in the various States as follows:

Pennsylvania.—Since 1900 the examination of the Pennsylvania coal field has been carried on through the cooperation of the State and Federal authorities, but the field work has been done entirely by the geologists of the United States Geological Survey. In this time very detailed surveys have been made of most of the Pittsburg coal region of the southwest corner of the State, of a large area in the eastern part of the bituminous coal field in Indiana, Cambria, and Clearfield counties, and a part of the Allegheny Valley, embracing an area of about 5,000 square miles.

All coal work in this State is under the general direction of George H. Ashley, who was assisted during the past year by W. C. Phalen, Edwin F. Lines, M. J. Munn, and Frederick B. Peck. Surveys were carried on in Cambria, Clarion, and Allegheny counties, and some of the results are given in this volume in papers entitled "Coal in the Clarion quadrangle, Clarion County, Pa.," by E. F. Lines, and "The coal resources of Johnstown, Pa., and vicinity," by W. C. Phalen.

Virginia-Kentucky.—A reconnaisance survey was made of a district in the central part of the Appalachian field under the general supervision of George H. Ashley. The building of a new branch line from the Chesapeake and Ohio Railway up Russell Fork of Big Sandy River to the Virginia line and the beginning of construction of the South and Western Railroad from the end of this branch to the Atlantic coast promises to open in the near future one of the largest and best tracts of coal land in the central Appalachian region. In order to be able to furnish information on this interesting and economically important region, a detailed reconnaissance was made by Ralph W. Stone, assisted by C. W. Dodge, on both sides of the Virginia-Kentucky State line, and the more important results will be found in three papers in this bulletin by Mr. Stone entitled "The Elkhorn coal field, Kentucky," "Coal mining at Dante, Va.," and "The Russell Fork coal field, Virginia."

Alabama.—For several years Charles Butts has been engaged in a close, detailed survey of the coal fields in the vicinity of Birmingham, including much of the Warrior basin. During the past year Mr. Butts was assisted by Chester W. Washburne, and the work was carried to the east into the Cahaba coal field. Time did not permit the survey of the entire field, but the northern part was examined thoroughly, and a brief account of the results of this work may be found in a paper by Mr. Butts entitled "The northern part of the Cahaba coal field, Alabama."

Illinois.—In Illinois the examination of the coal field is carried on both by the State Geological Survey and by the Federal organization, with the understanding that each shall supply to the other manuscript reports on the area or areas investigated. During the last year the work of the Federal Survey was confined to two 15-minute quadrangles in Gallatin, Saline, White, and Hamilton counties, and the results are embodied in a paper in this volume by Frank W. De Wolf entitled "Coal investigations in the Saline-Gallatin field, Illinois."

Arkansas.—A demand for more detailed information regarding the Carboniferous coal field of Arkansas than is contained in the reports of the State Geological Survey led the Federal organization to make an examination of this field in the early part of the past summer. The work was done by Arthur J. Collier, assisted by Carl D. Smith, Sidney Paige, and R. D. Mesler. This work is of especial value, inasmuch as it has established the identity of the principal coal beds at the east and west ends of the field, and has thrown considerable light on the distribution of the workable coals, a point that has been troubling the operators for a number of years. A brief account of this work is given by Mr. Collier in a paper entitled "The Arkansas coal field."

Montana.—The coal fields of Montana are probably more extensive than those of any other State, but they

are not well known except along the main lines of railroad where mines have been opened, either to supply fuel for locomotive uses or for the great copper smelters of the Butte region. The quality of the Montana coal is exceedingly varied, but as a rule only the better grades are being mined at the present time.

The most important piece of geologic work carried on in Montana during 1906 was the careful mapping of the Great Falls coal field by C. A. Fisher, assisted by W. R. Calvert, H. M. Eakin, A. J. Hazlewood, and J. D. Pollock. Geologically this field is most interesting, since the coal occurs in the Kootenai (Lower Cretaceous) formation, which is not known to carry coal in any other part of the United States, except possibly in the Black Hills region of South Dakota and Wyoming. The field was carefully mapped from Missouri River eastward along the foothills of the Little Belt Mountains as far as Stanford. A brief synopsis of the results is given in a paper by Mr. Fisher entitled "The Great Falls coal field, Montana."

The Bear Creek and Red Lodge fields of Carbon County were examined by N.H. Darton, who traced the Red Lodge group of coal beds for a considerable distance to the point where they are concealed by the overlying Tertiary rocks, and the Bridger coal bed from a point near the Wyoming line northward to Joliet. An account of this field by Mr. Darton is entitled "Coals of Carbon County, Mont."

The great lignite field of the eastern part of the State was examined by A.G. Leonard, assisted by W. R. Holgate and W. H. Clark. This party made an exploratory trip from Glendive to Miles City and thence northward by way of Jordan to Hell Creek on Missouri River. An account of this trip and of the coal beds and other strata exposed will be found in a paper by Mr. Leonard entitled "Coal fields of parts of Dawson, Rosebud, and Custer counties, Mont."

Wyoming.—Wyoming is one of the great coal-producing States of the Union. This coal is extensively developed along the Union Pacific and Oregon Short Line railroads at Hanna, Rock Springs, and Kemmerer. It is also mined to some extent at Glenrock and Big Muddy on the Chicago and Northwestern Railway and along the Burlington system at Sheridan and Cambria. In addition to these well-known localities, there are immense areas of coal land along Powder River from a point north of Casper to the Montana line, in the Bighorn Basin, in Uinta County north of Kemmerer, and in Carbon County west of Rawlins.

During the past year the Hanna field of Carbon County was rather thoroughly explored by A. C. Veatch, assisted by Max A. Pishel, Max W. Ball, and Spencer R. Logan. A brief account of this work is given by Mr. Veatch in a paper entitled "Coal fields of east-central Carbon County, Wyo."

C. E. Siebenthal made a hasty examination of the coal beds in the western part of the Laramie basin, and a brief account is given by him in a paper entitled "Coal of Laramie Basin, Wyoming."

During 1905, A. C. Veatch, assisted by A. R. Schultz, made an examination of the southern Uinta County field from the Utah State line to a point north of Kemmerer. A short account of this work appeared in Bulletin No. 285, and a full report is contained in Professional Paper No. 56, entitled "Geography and geology of a portion of southwestern Wyoming, with special reference to coal and oil." During the past year this work was carried northward by Mr. Schultz, assisted by E. Eggleston Smith. The country is exceedingly rough and mountainous, but the coal fields were mapped with considerable care as far as Snake River. This region is scarcely accessible at the present time and little is known regarding the coals, but in the event of the construction of a railroad line along Snake River it seems quite possible that much of

the area of this field would become accessible by branch lines from the main trunk system. A brief account of this field will be found in a paper by Mr. Schultz entitled "Coal fields in a portion of central Uinta County, Wyo."

In the central part of the State there is a large syncline of coal-bearing rocks which in most places is covered by Tertiary sediments to such a depth that it is not accessible, but here and there along the rim of the basin coal beds are exposed. This is the case in the vicinity of Lander, where there is a small coal field that was examined by E. G. Woodruff. A very brief account of this field is given by Mr. Woodruff in a paper entitled "The Lander coal field, Wyoming."

Colorado.—Through the explorations carried on by the Colorado Fuel and Iron Company and the development of mines in the best and most accessible fields, the coals of Colorado are perhaps better known than those of any other western State. Nevertheless, there are a number of areas about which little information can be obtained, and it has been the aim of the Geological Survey to explore these in advance of development.

The largest area of undeveloped coal lies in the northwestern part of the State, in Routt, Rio Blanco, Garfield, Pitkin, and Mesa counties. On the completion of the Denver and Northwestern (Moffitt) Railroad through Routt County the northern part of this great area, or the Yampa coal field, will be the first to be developed. This was examined in 1905 by N. M. Fenneman and Hoyt S. Gale, and a detailed report of their work appeared in Bulletin No. 297, entitled "The Yampa coal field, Routt County, Colo." A brief account was published also under the same title in Bulletin No. 285. During the last season this survey was extended southward across the anticline of Axial Basin to the Danforth Hills and thence along the Grand Hogback southeastward to Newcastle on Grand River. This work was done by

Mr. Gale, who was assisted by A. K. Adams, A. L. Beekly, and R. D. Crawford. A brief account of this work is given by Mr. Gale in a paper entitled "Coal fields of the Danforth Hills and Grand Hogback in northwestern Colorado."

Colorado-Utah.—The great Uinta Basin, which extends from the vicinity of Crested Butte, Colo., westward into Utah, continues in the latter State along the south side of the Uinta Mountains at least as far as Castle Gate. The center of the basin is deeply covered by Tertiary sediments, and at the western extremity these overlap the upturned edges of the coal-bearing rocks and conceal them so that the limit of the field in this direction is unknown.

It is generally understood that the Book Cliffs, which form the southern margin of this basin, are coal bearing, but little or no information outside of that furnished by the established mines has been available regarding the character of the coal or the number and thickness of the beds. To supply such data George B. Richardson, assisted by W. D. Neal and Leon J. Pepperberg, carried on a rapid reconnaissance during the last season from De Beque, on Grand River, Colorado, into Utah as far as the Sunnyside mine of the Utah Fuel Company, where connection was made with the work of Mr. Taff, who, during 1905, made a careful instrumental survey of the Book Cliffs field from the Sunnyside mine westward to Castle Gate, and then southward along the east front of the Wasatch Plateau as far as Mount Hilgard, in Sevier County. A report of Mr. Taff's work was published in Bulletin No. 285 under the title "The Book Cliffs coal field of Utah." A brief account of the results of the survey during last year is given by Mr. Richardson in this volume in a paper entitled "The Book Cliffs coal field between Grand River, Colorado, and Sunnyside, Utah."

Utah.—During the last year Joseph A. Taff, assisted by Carl D. Smith, examined the region about Pleasant Valley,

in the Wasatch Plateau, much more carefully than was possible during the previous year, and his report is embodied in a paper entitled "The Pleasant Valley coal district, Carbon and Emery counties, Utah."

The coal fields of Iron County in southwestern Utah, were hurriedly examined during the last year by Willis T. Lee, who visited them and procured samples for chemical analysis from the anthracite of the western extremity of the field and from the bituminous coal east of Cedar City. This is the most important field of the Southwest, as it is accessible from the San Pedro, Los Angeles and Salt Lake Railroad, and some day it may furnish fuel to most, if not all, of the desert region of the southern part of the Great Basin. A brief description of the field will be found in a paper by Mr. Lee entitled "The Iron County coal field, Utah."

New Mexico.—The largest coal field in New Mexico lies in the northeast corner of the Territory, but the coals in this field are not well known, being developed only at Durango, Colo., and Monero, N. Mex., on the northern edge, and at Gallup, on the southern edge of the basin. In Contributions to Economic Geology for 1905 F. C. Schrader[a] had a brief paper embodying the results of a rapid reconnaissance examination made by himself and M. K. Shaler along the eastern edge of the basin from Durango to Gallup. During the last year the work has been continued by Mr. Shaler, assisted by James H. Gardner. They made a careful examination of the western part of the field from Durango to the southern point of the basin, about 60 miles south of Gallup. The results of this work are contained in a paper by Mr. Shaler entitled "A reconnaissance survey of the western part of the Durango-Gallup coal field of Colorado and New Mexico."

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[a] The Durango-Gallup coal field of Colorado and New Mexico; Bull. U.S. Geol. Survey, No. 285, 1906, pp. 241-258.

In addition to the regular work noted above, the writer made a hasty examination of two small coal fields in the eastern part of the Territory—one at Capitan, in Lincoln County, and the other known generally as the Una del Gato field, in Sandoval County. A brief account of the latter is contained in a paper entitled "The Una del Gato coal field of Sandoval County, N. Mex.," and of the former in a paper entitled "Coal in the vicinity of Fort Stanton Reservation, Lincoln County, N. Mex."

California.—In general the coals of California are of so low a grade as to be unable to stand in competition with fuel oil. As a consequence many of the miners have suspended operations. From time to time during the last few years reports have been made of the occurrence of a better grade of coal in Stone Canyon, in the southeastern part of Monterey County. In 1905 Ralph Arnold visited Stone Canyon and determined the geologic relations of this coal bed. A brief account of his work appeared in Bulletin No. 285, entitled "Coal in the Mount Diablo Range, Monterey County, Cal." During the past summer the writer found opportunity to visit this mine, and a short account of the results of the examination, as well as of those obtained from a chemical analysis, is contained in a paper entitled "Coal of Stone Canyon, Monterey County, Cal."

TECHNOLOGIC WORK.

The technologic work on fuels is under the direction of Joseph A. Holmes. Up to the spring of 1907 the work of this branch has been carried on largely at St. Louis, Mo., where it was started in connection with the exposition in 1904. The principal work of the branch has been the testing of carload samples of coal, and in order to do this systematically it was necessary for an inspector to supervise the loading of cars, and as a check to take samples from the mine furnishing the carload lot. During the last year this work has been under the charge of

J. Shober Burrows, who has made an extended study of methods of sampling and the results to be obtained therefrom. A brief account of these results and a discussion of their meaning is given by Mr. Burrows in a paper entitled "The importance of uniform and systematic coal-mine sampling."

One of the most important results of the various tests for the better utilization of the fuel resources of the country is the demonstration that producer gas for power purposes can be made successfully from all grades of bituminous coal, lignite, and even peat. The results of these tests point conclusively to the substitution of producer-gas plants and gas engines for the generation of power in place of the wasteful steam engine in general use at the present time. The end of the steam engine is nearly in sight, and many people are wanting information regarding the present status of the producer and gas engine, in expectation of their installation in the near future. In order to supply unbiased information to the public on this important subject, R. L. Fernald, professor of mechanical engineering, Washington University, St. Louis, Mo., who has had charge of all tests made at the fuel-testing plant on the gas producer and gas engine, has prepared a brief statement which will be found in a paper entitled "The present status of the producer-gas power plant in the United States."

Another field of investigation which promises to have a distinct bearing on the better utilization of our coals is that of briquetting, and the present condition of the briquetting industry is summarized by Edward W. Parker in a paper entitled "Condition of the coal-briquetting industry of the United States."

* * * *

DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

GEORGE OTIS SMITH, DIRECTOR

BULLETIN 383

NOTES

ON

EXPLOSIVE MINE GASES AND DUSTS

WITH SPECIAL REFERENCE TO

EXPLOSIONS IN THE MONONGAH, DARR, AND NAOMI COAL MINES

BY

ROLLIN THOMAS CHAMBERLIN

WASHINGTON
GOVERNMENT PRINTING OFFICE
1909

CONTENTS

	Page
Introduction	5
Charter of the report	5
Explosions studied	6
Gases found in the mines	7
Methods of collecting	7
Analyses	8
Methane	9
After damp	11
Deficiency of oxygen	15
Possible conditions of gas in coal	16
Liberation of gas by crushing coal	17
Plan of experiments	17
Method of crushing	18
Detailed results	18
Gases from coal bottled in a vacuum	24
Vacuum bottles	24
Volume of gas	24
Character of gas	25
Comparison with mine gases	31
Rate of escape	33
Practical significance of rate	36
Effect of barometric changes	37
Gases obtained by heating coal	39
Studies on coal dust	42
Evidence that dust took part in explosions	42
Character of dust deposits	44
Dust samples	45
Explanations of dust effects	46
Cause and manner of coking	48
Loss of volatile matter	49
Comparison of other dust samples	51
Restraining factors—shale and dampness	52

CONTENTS—Continued

	Page
Practical considerations as to danger of explosions	54
Influence of seasonal change	54
Effect of shale dust on explosions	55
Comparative inflammability of old and fresh coal dusts	56
Supposed danger in old dust	56
Tests on differently exposed samples	57
Significance of tests	58
Absorption of oxygen by coal	60
Decrease in combustible gases	62
Conclusion—fresh dust more dangerous	63

ILLUSTRATION

FIGURE 1. Diagram showing rates of escape of methane from coal 34

NOTES ON EXPLOSIVE MINE GASES AND DUSTS, WITH SPECIAL REFERENCE TO EXPLOSIONS IN THE MONONGAH, DARR, AND NAOMI COAL MINES.

By Rollin Thomas Chamberlin.

INTRODUCTION.

CHARACTER OF THE REPORT.

The studies herein reported were begun as a part of researches undertaken by the United States Geological Survey looking to the more efficient utilization of the coal in the United States through the reduction of waste in its extraction, and were continued as part of further researches having regard to the conservation of the fuel resources of this country and to the lessening of injuries and fatalities in coal mining.

Among other phases of the general problem to be studied were the origin of the gas which escapes into coal mines, its modes of occurrence in the coal and rock strata, and the conditions governing its outflow into the mines. The subject of relative danger from destructive explosions due to gas and coal dust in different mines belonging to different coal fields was to be one of the principal lines of investigation.

But this work was barely under way when the series of unusually disastrous explosions in the Naomi, Monongah, and Darr mines of Pennsylvania and West Virginia, in December, 1907, afforded an exceptional occasion to observe the behavior of explosions on a large scale. Because of the opportunities for study afforded by these terrific explosions, the inquiry originally planned was diverted to the more specific investigation of the conditions

in these mines, and the examinations have been directed toward finding those qualities of gas and dust which were concerned in these explosions. The following discussion, therefore, consists essentially of a report on that subject; but it is far from being exhaustive, and is to be regarded as a preliminary outline of investigations which are still in progress.

EXPLOSIONS STUDIED.

The first of the three mine explosions mentioned occurred in the Naomi mine of the United Coal Company, near Bellevernon, Pa., on Sunday, December 1, at 7:40 p. m. All the men who were within the mine at the time, fortunately only 34, were killed.

Less than a week later there occurred in mines Nos. 6 and 8 of the Fairmont Coal Company at Monongah, W. Va., the most disastrous mine explosion yet recorded in the annals of American mining. The mines were comparatively new and well laid out. Mine No. 8 had been in operation only about two years and was the pride of the Fairmont Coal Company. Mine No. 6 was first opened about four years earlier. In order to make it possible, in case of emergency, for either mine to be ventilated by the ventilating system of the other, the two sets of workings were connected underground. The F face heading of mine No. 6 led directly into No. 2 north heading of No. 8 mine. On Friday, December 6, at about 10.30 in the morning, an explosion of unusual violence swept completely through both mines, pursuing its course throughout the numerous ramifications and bursting out of the two pit mouths, located 1¼ miles apart, nearly simultaneously. The slope of mine No. 6 was only slightly damaged, but at the mouth of No. 8 the destruction was very great. The fan was wrecked, the engine house was demolished, and mine timbers were blown across Monongahela River. As nearly as can be determined, 361 men were killed in the two mines by the explosion.

While the inspection of the Monongah mines was still in progress, on Thursday morning, December 19, at about 11.20, a similar explosion wrecked the Darr mine of the Pittsburgh Coal Company at Jacobs Creek, Pa.; 238 men lost their lives in this explosion, which in number of casualties is second only to the Monongah disaster in the history of American mining. Of all the men in the mine at the time of the explosion, only one man, who happened to be within 100 feet of the surface on an old manway in a wet, unexploded portion of the mine, succeeded in escaping alive.

The underground investigation of these mines was made in cooperation with Clarence Hall and Walter O. Snelling, of the United States Geological Survey, and James W. Paul, now of the Survey but at that time chief of the department of mines for West Virginia, to all of whom the author is greatly indebted for valuable assistance, suggestions, and advice. Mr. Paul will report on the nature of these explosions, the precipitating causes, their destructiveness, and the general conditions in these mines following the disasters. The present report is confined essentially to the laboratory examination of some of the explosive materials collected from these mines directly after the explosions.

GASES FOUND IN THE MINES.

METHODS OF COLLECTING.

As soon as practicable after these explosions samples of the mine atmosphere were collected at the coal faces and from the return air ways in various parts of the mines. It was hoped that something as to the nature of the after damp might be determined, but as the exploration of the mines could be carried only where there had been a certain amount of ventilation, the samples of after damp were necessarily greatly diluted with air. With the aid of breathing helmets and compressed-air cylinders attempts

were made to collect after damp in the tight places where there appeared to have been little ventilation, but the subsequent analyses have shown that the proportion of after damp remaining was small. Other samples were taken to determine the accumulation of fire damp in the workings.

The samples of air and gas from these mines were collected for analysis in glass tubes of 125 cubic centimeters capacity. These tubes were drawn out to a 5-millimeter bore at each end, over which was slipped a piece of red antimony rubber tubing 5 to 6 cenitmeters in length. Before entering the mine each tube was filled with water, and a tight-fitting plug of glass rod was inserted in the rubber tubing at each end. To take a sample of the mine air the glass plugs were removed from the ends of the tube, allowing the water to run out and be replaced by air, after which the ends of the tube were securely closed by the plugs and the rubber connections tightly wired with copper wire. Glass tubes thus sealed were found to hold gas samples for several weeks without apparent change from leakage or diffusion. However, as a thin film of water always remains upon the walls of the tube when the gas is collected in this manner, it is inevitable that a small amount of carbon dioxide be absorbed. Haldane[a] has called attention to the fact that when gas samples are collected in glass tubes whose walls are moist, a small amount of carbon dioxide is absorbed by the sodium silicate of the glass. If the water used be clear, the gas sample loses a small amount of carbon dioxide, but if the water used be dirty, the sample may gain carbon dioxide from the action of bacteria. The samples of gas collected in the Naomi, Monogah, and Darr mines are all subject to these criticisms. Clear water was used in every tube but one, No. 26, which had to be refilled from a pool of standing water in the mine.

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[a] Foster, Sir Clement, and Haldane, J. S., The investigation of mine air.

Whenever the sample could not be analyzed within a few days after it was collected, the rubber connections were completely coated with paraffin, thus preventing with certainty any passage of gas through the rubber.

The samples of gas obtained from these mines were for the most part selected either from points in the workings where there appeared to be unusual quantities of fire damp, or where the presence of after damp was suspected. Other samples were collected from the return air currents to obtain information upon the general character of the air throughout certain sections of the mines. Except in one or two special cases, the samples were collected just below the roof, in order to obtain a proportion of methane somewhat near the maximum present in the air. This was thought desirable because the gas near the roof would be most likely to be ignited from an open light upon a miner's cap, and because the maximum percentage of marsh gas in an entry gives the best indication of the danger from gas.

ANALYSES.

The analyses of the samples of gas collected within these three mines are given in the table which follows. The first 18 analyses were made according to the technical method of gas analysis described by Hempel.[a] The remainder of the analyses, with the exception of Nos. 23 and 29, were carried on over mercury in the apparatus devised by Professor Bone, of the University of Leeds.[b]

Analyses of samples of gas taken in Monongah, Naomi, and Darr mines.

[Tabular Matter Omitted]

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[a] Hempel, W. M., Methods of gas analysis, 1902: technical method.

[b] *Bone*, W. A., Jour. Soc. Chem. Ind., vol. 27, 1908, pp. 10-12.

METHANE.

It will be seen from the table that the highest percentages of methane (CH_4) were usually found in the samples collected at the faces of some of the mains. Methane in such high percentages occurred only more or less locally, either at the high points in the roof where, owing to its extreme lightness, it had accumulated, or as a thin stratum of fire damp floating along beneath the roof of an entry for a short distance from the coal face. Generally the diffusion of the gas was found to have taken place slowly in tight places where the current of air was slight, so that at a few rods from the face the percentage of methane in the air, even at the roof, was much reduced, while at the floor there was still less methane.

But in some places the gas was found to have become far more evenly distributed throughout the entries. In several of the entries in the Darr mine (see analyses 21, 22, 24, and 26) fire damp was detected in such quantities by the Wolf lamp, at distances of 75 to 100 feet from the coal face, that it was not thought advisable to push on to the faces even with safety lamps. Later, with an electric flash light to illumine the way, the faces of two of these three entries were visited. Tube 28, filled with air on January 4, 1908, from the face of No. 12 right butt, off entry 27, contained 7.99 per cent of methane, while tube 26, filled on January 2 at a point 80 feet from the face of this same entry, contained 4.24 per cent of methane. The conditions were similar at the face of the main entry. Tube 21, filled with air from the roof of the main entry, 5 feet inby the third right crosscut, inby entry 30, contained 4.99 per cent of methane, while tube 22, filled a few minutes later at a point 20 feet inby the fourth right crosscut (about 60 feet from the face of the main), contained 6.01 per cent of methane. Two days later a sample of gas (No. 27) was taken from the mouth of a drill hole 5 inches in diameter in the face of the right air course of the main entry. In this methane amounted to 32 per cent.

These figures show that the percentage of methane in the air near the roof of the gassy entries diminished rapidly with increasing distance from the face. This was true even in entries where the diffusion has been fair, for the Wolf lamp at the point where tube 21 was filled indicated gas as low as 2 feet above the floor. The high percentages of methane were chiefly local. The main return air currents, and in general those parts of the entries distant from the coal face, contained methane only in very much smaller proportions. In these passageways the gases had become more thoroughly mixed by diffusion as well as diluted in the draft of air, and hence here it made less difference whether the sample for analysis was collected at the roof or near the floor. An example of this was shown in No. 1 left butt, off entry 30, in the Darr mine. Tube 20, filled at the roof of the entry 20 feet inby from entry 30, showed only 1.55 per cent of methane. At this point a Wolf lamp on a tie showed a ¼-inch gas cap, indicating from 1 to 1.5 per cent of methane. As only a very slight current of air was moving out of this entry, the thorough mixing of the gases was apparently due largely to steady diffusion rather than to the air draft. Tube 29, filled with gas-laden air from the roof of entry 28, Darr mine, about 125 feet inby No. 1 left butt, contained 2.12 per cent of marsh gas. On the floor just below nearly a ⅓-inch gas cap was got with a Wolf lamp. The air was moving slowly.

In the main return air ways the fire damp was more diluted. On December 21, two days after the explosion in the Darr mine, when the ventilation was bad, the air from the return air way just inside of the first crosscut to the left, inby from the swamp entry, contained 2.51 per cent of methane (analysis 17); but the air at this same point on January 1, when the ventilation was better, contained only 1.50 per cent of marsh gas (analysis 18). On January 2 the return air from the swamp entry showed only 0.58 per cent of methane (analysis 23). Two days later a Chesneau lamp registered 1.4 per cent of fire

damp where tube 18 had been filled, and 0.4 per cent in the return air from the swamp entry, indicating that, while there had been a slight improvement in the character of the air within these two days, the figures for tubes 23 and 18 are probably not far from the normal conditions. Where the Chesneau lamp registered 1.4 per cent of fire damp on January 4, and the chemical analysis of gas collected January 2 gave 1.50 per cent, the Wolf lamp on each occasion showed a ¼-inch gas cap.

In the Naomi mine, where very high percentages of methane were found at some of the entry faces, the main return air current on the center main, 1,800 feet from the mouth of the slope, contained, on the afternoon of December 14, 1907, only 0.75 per cent of marsh gas (analysis 16).

At Monongah there appears to be much less gas in the mines, both locally near the coal face, and in the return air in particular. In mine No. 6 the air of the main south return air way, 50 feet from the bottom of the shaft leading to the fan (analysis 9), and another sample from the main right return air way, 200 feet inby a face entry (analysis 10), contained, on December 16, 1907, only 0.22 and 0.45 per cent of methane, respectively. In mine No. 8 a test of the air collected on December 12 from the return air way opposite room 15 on the fifth right, off second north heading, showed only 0.09 per cent of methane (analysis 3). However, instead of collecting the gas from near the roof, the tube in this case was filled at a point about midway between the floor and the roof.

AFTER DAMP.

In all the samples of mine air collected in the Monongah, Naomi, and Darr mines within a few days after the explosions, the percentage of carbon dioxide greatly exceeded that of carbon monoxide. But it is true that none of these samples was collected until a fair state of ventilation had been reestablished after the explosions, such

that parties could remain in the mines for several hours. The best of the samples was No. 17, taken from the Darr mine by Clarence Hall on the afternoon of December 21, two days after the explosion. While obtaining this sample three of the party were so overcome as to be forced to leave the mine. An analysis of this air showed 1.07 per cent of carbon dioxide and 0.61 per cent of carbon monoxide. No other sample approached this one in respect to the prominence of carbon monoxide, but even in this one the after damp was much diluted with air.

It may be instructive to undertake a rough calculation to show approximately what proportion of after damp is really present. Assume that essentially all of the oxygen of the air in the exploded portion of the mine was consumed in the explosion, and that carbon monoxide was formed because of insufficient oxygen, either directly or from the reduction of carbon dioxide by the floating particles of incandescent coal dust. Before making a computation of the proportion of after damp, it is necessary to decide to which of these reactions the carbon monoxide is to be assigned, as it makes a difference in the total resulting amount of carbon monoxide whether the monoxide be formed directly from the partial combustion of the gas or through the reduction by the glowing particles of coal dust of a portion of the carbon dioxide produced in the explosion.

Beard,[a] quoting Thomas, states that the explosion of a mixture of methane and air at the most explosive point (methane 9.57 per cent, air 90.43 per cent) produces no carbon monoxide, but that as the percentage of methane is increased above the point named carbon monoxide is formed in ever-increasing proportion until, at what he gives as the explosive limit, 16.67 per cent of methane in air, the result of an explosion would be 87 per cent monoxide and 13 per cent dioxide; while near the limit of inflammability, 29 per cent methane, no carbon dioxide

[a] *Beard*, J. T., Mine gases and explosions, 1908, p. 130.

is formed. He writes the equation $2CH_4+O_2+4N_2=2CO+4H_2+4N_2$.

Agreeing with this in a measure is the statement of the French fire-damp commission that the explosion of a mixture of methane and air, containing 12 per cent of methane, gave rise to the following gases: Carbon dioxide, 4.8 per cent; carbon monoxide, 3.9 per cent; methane and other hydrocarbons, 2.5 per cent; hydrogen, 3.5 per cent; nitrogen, 82.2 per cent; total, 96.9 per cent.

At variance with this, Broockmann concludes from his own experiments with the products of combustion of methane and air that a pure fire-damp explosion gives no carbon monoxide.[a] A mixture of air and fire damp containing from 10.8 to 13.5 per cent of marsh gas he found to give two separate flames. Expecting to find some carbon monoxide formed as the result of the first flame, Broockmann removed the products of the first combustion, in an exploding mixture of methane and air, before the appearance of the second flame, but in no case found a trace of carbon monoxide. Instead, the heat of the first combustion converted the unconsumed methane into acetylene and hydrogen. These doubtless furnish the fuel for the second flame.

Heise and Herbst also state[b] that a pure gas explosion never produces carbon monoxide, and that an explosion of air containing more than 9½ per cent of methane produces, along with steam, only carbon dioxide. Differing somewhat with Broockmann, they state that the two elements, carbon and hydrogen, which are combined in CH_4 become separated only when sufficient oxygen is present for the complete oxidation of both elements. Otherwise the compound does not allow itself to be split up.[c]

[a] Broockmann, Niederrheinisch-WestfiilischenSteinkohlenbergbaues, vol. 6, p. 52.

[b] Heise and Herbst, Bergbaukunde, vol. 1, 1908, p. 448.

[c] Idem, p. 463.

For the computation in the case in hand (analysis 17) it will be assumed that the carbon monoxide has not been produced directly from a partial combustion of methane and other hydrocarbon gases, but has resulted from a reduction of the carbonic acid by the particles of incandescent coal dust, according to the reaction $CO_2+C=2CO$. The analysis of the return air showed 1.07 per cent of carbon dioxide. From this are to be deducted both the percentage of carbon dioxode in the air, 0.03 per cent, for the after damp has been much diluted since the explosion, and also the carbon dioxide exhaled from the coal during that time. A rough estimate of the latter can be made, as the analyses of the gas issuing from the coal in the form of feeders and blowers, as well as from coal bottled in a vacuum, show that the proportion of carbon dioxide to methane in the gas escaping from the fresh coal of these mines is 1 or 2 to 100. As the percentage of methane was found to be 2.51, the amount of carbon dioxide which the fresh coal has contributed to the air since the explosion may be taken to be 0.03 per cent. This is the proportion of carbon dioxide to methane in the gas from fresh coal. In the older workings of the mine the proportion of the dioxide is greater than this; but in the absence of data upon the ratio of these gases escaping from coal which has long been exposed to the air, no allowance is here made for the greater proportion of carbon dioxide in the old entries. This leaves 1.01 per cent of carbon dioxide to be assigned to the after damp produced by the explosion.

To produce 1.01 cubic centimeters of carbon dioxide and 0.61 cubic centimeter of carbon monoxide from an explosion of methane, in cooperation with coal dust whose heated particles cause the formation of the monoxide by abstracting oxygen from a portion of the dioxide, 2.63 cubic centimeters of oxygen would be consumed, providing that all the hydrogen of the methane was burned to water.

This computation does not take into account the fact that, in addition to methane, other hydrocarbons participated in the explosion. These necessarily consisted of relatively more carbon than CH_4. But, on the other hand, the coal-dust particles which caused the reduction of the dioxide to the monoxide, instead of being pure carbon, contained a certain proportion of hydrogen, a portion of which was probably oxidized to water. These two factors tend to offset each other. Because of their complexity they can not be further treated here.

On the supposition that no carbon dioxide was absorbed by the water in the mine, and that all the oxygen in the air was consumed in the explosion, the volume of the oxides of carbon in the sample collected should bear the same relation to the amount of CO_2+CO originally developed by the explosion as the corresponding volume of oxygen, 2.63, does to 20.5, the percentage of oxygen which is assumed to have been originally present in the mine. This figure is taken because the coal rapidly absorbs oxygen from the air. The average proportion of oxygen in the air of tight places in this mine was found by a calculation from the analyses to be only 20.08 (see p. 15); but 20.50 would seem a better figure for the average of the mine air as a whole. The ratio $\frac{2.63}{20.5}$ is equal to 0.128, or from 12 to 13 per cent of after damp in the sample collected.

However, this can at best be only a rough estimate, as several uncertain factors are involved. The mine air previous to the explosion contained a small and unknown quantity of carbon dioxide. But on the other hand, some carbon dioxide has doubtless been absorbed by the water in the mine since the explosion. In a measure these factors tend to offset one another. It is also true that other hydrocarbons, in addition to methane, were consumed in the explosion, and these would unite with oxygen

in different proportions. But methane in all probability contributed most.

While this sample of the air from the Darr mine after the explosion shows that carbon monoxide may reach a considerable percentage in after damp, the other samples of the mine air which, however, were collected after better ventilation had been established, showed the presence of much less carbon monoxide, even though the proportion of the dioxide in some samples amounted to 1 per cent. It seems probable that some and perhaps most of the difference was due to more thorough ventilation before the later samples were collected, for carbon monoxide, once removed, would not be resupplied except in very small quantities, but carbon dioxide might have been supplied from the coal, the lamps, etc., since the explosion.

However, the relative proportions of carbon dioxide and carbon monoxide in after damp must always be variable, depending on the ratio between the available oxygen and the available combustible matter, gas and dust, in the air. If the explosion were due largely to methane in the air, in quantities not exceeding 10 per cent, and with little dust as an accessory, little carbon monoxide would be formed. But, on the other hand, in a dust explosion where large quantities of coal dust are present, capable of distilling volatile hydrocarbons in volumes too great to be entirely consumed by the quantity of oxygen in the mine air, and where there is an abundance of hot coal dust stirred up in the air, carbon monoxide might, perhaps, be produced in greater quantities than the dioxide. A coal-dust exploion is more complex than one of fire damp. If the explosion of the dust proceeds by rapidly feeding the flame with combustible gases and hydrocarbon vapors derived from it through the influence of the heat. as is believed to be the case, there is, at first, sufficient oxygen at hand to insure the complete oxidation of the gases developed. Carbon dioxide and steam result. But under ordinary conditions, with plenty of dust, the distillation of volatile matter continues, liberating an excess

of readily available combustible gas which, because of insufficient oxygen, is only partly consumed. In the absence of oxygen, a portion of the carbon dioxide already produced is reduced to carbon monoxide in variable proportions, depending on the amount of red-hot dust floating in the atmosphere and the length of time during which the dust remains sufficiently heated to allow the reducing reaction to proceed.

DEFICIENCY OF OXYGEN.

In order to ascertain the character of the mine air, irrespective of the after damp, a recalculation of the analysis was made. The analyses of gas from mine feeders and from coal bottled in a vacuum show that the proportion of carbon dioxide to methane in the gas escaping from the fresh coal of these mines is 1 or 2 to 100. Wherever methane is found in the mines it is safe to assume that a volume of carbon dioxide corresponding to 1 per cent of the methane has escaped from the coal simultaneously with the marsh gas. This figure, plus the 0.03 per cent of carbon dioxide in normal air, is subtracted from the percentage of carbon dioxide in the analysis. To be on the right side, it is assumed that all the rest of the carbon dioxide has been produced by the oxidation of CH_4, as the combustion of this compound consumes more oxygen per unit of carbon dioxide formed than any of the other compounds which could have participated in the explosion. The amount of oxygen which would have been required, on the basis of an explosion of methane, to yield the oxides of carbon found in the analysis, is then added to the percentage of oxygen shown by the analysis. The percentage of methane in the analysis, plus the carbon dioxide of normal air and that which, on the basis of the methane present, has been considered to have been derived from the coal since the explosion, is deducted from the total, and the remaining figures recalculated so as to add to 100.

This gives an estimate of the percentage of oxygen in the mine air irrespective of the after damp from the explosion and the feeder gas which has escaped into the workings from the coal since the explosion. Because of the assumptions, these estimates give a generous figure for the percentage of oxygen. An average of the three analyses of air from the Naomi mine made in this way was 20.86 per cent, eleven analyses from the Monongah mine gave 20.72 per cent oxygen, and thirteen analyses from the Darr mine gave an average of only 20.08 per cent oxygen. These figures indicate a deficiency of oxygen in the mine air which can not be attributed to the formation of free carbon dioxide or carbon monoxide, unless it be supposed that much of the carbon dioxide formed has been absorbed by water in the mine, which seems improbable in these dry mines. Instead, it would appear that the coal has absorbed oxygen from the air, thus reducing the percentage of that gas and increasing that of nitrogen.

The greatest deficiency in oxygen occurred in the sample of gas-laden air collected near the face of the swamp entry in the Darr mine (analysis 25). Corrected for carbon dioxide and methane, this sample showed the unusual proportions, oxygen 16.13 per cent and nitrogen 83.87 per cent. This sample was also characterized by the highest proportion of methane (50.67 per cent) obtained in these mines. That the diffusion of the air and gases in this cleft in the roof had progressed slowly is shown by the accumulation of so much fire damp, and it was apparently because of the stagnancy of the air in this nook that the coal was able to abstract such a proportion of the oxygen. It must be noted that feeder gas often contains several per cent of nitrogen, so that with 50 per cent of methane (feeder gas) present in the air a part of the apparent excess of nitrogen and deficiency of oxygen may, perhaps, be explained by this nitrogen coming from the coal.

As many of the samples of air which have contributed to these averages, particularly those from the Darr mine, were collected from sheltered, poorly ventilated nooks in order to get data on the accumulation of fire damp, the low figure of 20.08 per cent for oxygen is not representative for the air of the mine as a whole. While the loss of oxygen is less conspicuous in the general mine air than in pockets in the roof and in tight places where there is little air stirring, its effect is felt throughout the mine, and furnishes an additional reason for ventilation which will afford a continuous supply of good air, as well as remove the dangerous fire damp and the noxious products of combustion.

POSSIBLE CONDITIONS OF GAS IN COAL.

The gas which escapes from coal may exist within the mass of the coal in three possible conditions. It may be mechanically held or imprisoned in minute pores, cavities, or cracks throughout the coal; it may be occluded or dissolved within the substance of the coal; or it may be the result of slowly operating chemical reactions, such as those which have produced the coal from the original vegetable matter and which, still operative, might, as a working hypothesis, be supposed to generate gas in proportion as it is given off. In the first two cases the gases are supposed to be already existent within the coal as gases; under the third hypothesis they are to be regarded as now produced for the first time by chemical decomposition of the solid coal substance. The ultimate source of the gases may be taken as the same under each hypothesis, for there can be little doubt that the bulk of the gas given off from coal has arisen from the slow decomposition of organic matter as a by-product in the process which has converted vegetable humus into coal. The first hypothesis favors the belief that the gas-generating process has been very slow and that such gas as comes off at the present time has long been stored in minute cavities or pores, from which it escapes when the

coal is fractured, as in mining operations. The second hypothesis assumes, like the first, that the gas was developed long ago, but differs from it in assuming that the gas, as fast as it was developed from the coaly matter, was retained within the coal substance in solution, or occluded, instead of being held mechanically in minute crevices and cracks. This hypothesis is suggested by the well-known property of various metals to occlude or dissolve within their mass certain gases, and by the familiar power of charcoal to condense on its surface or absorb many times its own volume of various gases. The term occlusion, which Graham gave to this imperfectly understood property of certain metals to absorb particular gases, has been very loosely used, especially in mining literature, where "occluded gas" usually means gas held according to either of the first two hypotheses, the radical differences between them having generally been overlooked. By some writers, indeed, the term is intended to carry the idea of the first hypothesis alone, the second, that of true occlusion, being left out of account.

The third idea is only a working hypothesis which is framed to recognize the possibility that the coal-forming, gas-generating process is still in progress, and that the escape of the gases is a sort of index of the present chemical activity within the coal.

LIBERATION OF GAS BY CRUSHING COAL.

PLAN OF EXPERIMENTS.

To throw light on this possible threefold state in which the gases are held in coal, and to determine the relative importance of the three hypotheses, a series of experiments was devised. In the first the coal was broken up and crushed to a coarse powder in an air-tight receptacle, from which any gas liberated during the process of crushing can be extracted by a vacuum pump. Only such gas as was already stored in the coal can be freed by crushing it, as the process is accomplished very quickly. How much gas might be expected to be freed from a state of

true occlusion by crushing is less clear. The most thoroughly studied form of occlusion is that of hydrogen by palladium. Whether palladium charged with hydrogen will give off part of its gas at the ordinary temperature when placed in a vacuum depends entirely on the condition of the metal. If the palladium is in a very finely divided state, a considerable portion of the hydrogen is given off when the pressure is greatly reduced;[a] but the cast or forged metal gives off no hydrogen whatever when placed in a vacuum at ordinary temperatures.[b] The hydrogen begins to be evolved from the solid metal only at temperatures above 100° C. It is conceivable that reducing the size of coal fragments by crushing in a vacuum might, in some similar way, allow the evolution of gas which was not possible from the lump coal. But as the lumps of coal are only crushed down to a coarse powder it would not seem as if truly occluded gas should be freed, to any large extent, by the coal crusher, even in a vacuum. If crushed under full atmospheric pressure in an inert gas, no occluded gas should be liberated. It is not at all certain that coal behaves like palladium in these matters. It seems, therefore, safer to conclude that by crushing the coal and opening up many pores and cavities it is chiefly the imprisoned cavity gas that is liberated.

METHOD OF CRUSHING.

The apparatus for crushing the coal was constructed on the principle of the familiar steel mortar, fitted with a long piston rod incased in a heavy rubber tubing, which, with one end fastened to a flange at the top of the mortar cylinder and the other wired to the piston rod near its free end, makes an air-tight connection, and at the same time renders the piston movable. A few vigorous blows delivered with a heavy mallet upon the end of the piston rod serve to crush the coal, after which the

[a] Moissan, Chimie minérale, vol. 5, p. 860.

[b] Graham, Chemical and physical researches, pp. 283-290.

gas liberated during the crushing is pumped out of the cylinder through a short delivery tube, fitted with a stop-cock.[a] The apparatus is intended to maintain a complete vacuum for the short time required to crush a sample of coal, but in practice it was found advisable, in order to prevent a slight inleaking of air, to place the cylinder of the crusher in a pail of water during the operation. This crusher was able to pulverize from 50 to 100 grams of coal at a time. The coal was crushed both in a vacuum and under full barometric pressure.

DETAILED RESULTS.

Sample 1.—Coal collected on December 13, 1907, from the face of No. 4 right entry, off the F-face heading, mine No. 6, Monongah, was crushed in a vacuum on January 27, 1908. Starting with lumps of coal of about 1 cubic inch, the material was crushed twice, the crusher being opened after the first crushing and the finer dust sifted out. The extent to which the coal was reduced after both crushings was determined by sieves, as follows: Of 100.21 grams of coal used, 20.56 grams passed through a 30-mesh sieve, 31.26 grams passed through a 10-mesh sieve, and 48.39 grams was too coarse to pass the 10-mesh sieve. There was obtained 10.57 cubic centimeters of gas at 0° C. and 760 millimeters pressure, having the following composition:

Analysis of gas obtained by crushing coal sample 1

	Per cent
Carbon dioxide	2.90
Methane	39.65
Oyxgen	10.07
Nitrogen	38.11
Nitrogen (excess)	9.27
	100.00

[a] This rock crusher has been described in detail, with a diagrammatic sketch in The gases in rocks: Carnegie Institution of Washington, Pub. No. 106, p. 39.

If the gas all came from the coal which passed through the 30-mesh sieve, the methane would amount to 0.26 of the volume of that coal. The latter figure is to be preferred.

Sample 2.—Coal collected December 12, 1907, from room 3 on third right, off second north heading, mine No. 8, Monongah, was crushed in a vacuum January 28, 1908. Two lumps of coal were pulverized, in two crushings, to the following degree of fineness: Of 49.13 grams in all 20.24 grams passed through the 30-mesh sieve, 23.67 passed through the 10-mesh sieve, and 5.22 grams was too coarse to pass the 10-mesh sieve. The crushing liberated 11.71 cubic centimeters of gas at 0° C. and 760 millimeters pressure, which had the following composition:

Analysis of gas obtained by crushing coal sample 2

	Per cent
Carbon dioxide	1.56
Methane	40.99
Oyxgen	9.86
Nitrogen	37.62
Nitrogen (excess)	10.27
	100.00

The quantity of methane is equivalent to 0.30 of the coal which passed the 30-mesh sieve, to 0.14 of the volume of the 10-mesh coal, and to 0.12 of the volume of all the coal used.

A duplicate test with this same sample of coal, crushed in three trials, afforded the observation that there is not any very noticeable slackening in the gas obtained from the second and third crushings. For the first trial the total weight of coal is used. After the gas has been pumped over into the receiver, the crusher is opened and the fractured coal sifted with both the 10-mesh and 30-mesh sieves. Only the coal coarser than the 10-mesh sieve is returned to the cylinder of the crusher for the second trial. The second trial thus crushes coal fragments

averaging about the size of a bean to fine 10-mesh coal and dust, and as it crushes about the same weight fine enough to pass through the sieves as did the first trial, it is to be expected that about the same volume of methane will be obtained. After the second trial the coal is again sifted and that portion which is too coarse to pass through the 10-mesh sieve is put back into the crusher for the third trial. It is clear that some of the gas comes from that coal which is partly crushed, though not fine enough to go through the 10-mesh sieve, but in estimating the volume of gas given off per unit volume of coal it seems advisable to consider only that coal which has passed through the sieves, for whatever gas may have come from the coarser coal would undoubtedly be offset by the gas still remaining in the fine coal. Crushing coal to 30-mesh does not remove all the gas.

In the experiments with samples 1 and 2 the coal was crushed in a vacuum and the gas brought out under reduced pressure. To ascertain the part played by low pressure in this process of gas extraction, and hence whether much gas escaped from occluding bonds, samples of coal were crushed under the full barometric pressure, both in air and in an atmosphere of carbon dioxide.

Sample 3.—Coal from the same can as sample 1 (p. 18) was crushed in air under full barometric pressure. As it was necessary in this experiment to discover how much methane is liberated solely by crushing the coal, without the cooperation of a reduction in pressure, the gas was removed from the crusher in two portions. The first portion consisted of the air and gas which was removed by the first stroke of the vacuum pump. The stopcock being open only about two seconds, and only about half the contents of the crusher being removed, whatever methane was found in this portion must have been freed from the coal without the influence of reduced pressure. As soon as this portion could be stored away for analysis,

the remaining gas was rapidly pumped out of the crusher. These two portions were analyzed as follows:

Gases removed after crushing coal sample 3 in air, with their relation to the coal by volume.

[Tabular Matter Omitted]

As would naturally be expected, the percentage of methane is higher in the second portion than in the first, though the difference is not great. But the greater amount of methane in the second portion was not liberated entirely through the influence of reduced pressure, as the fine coal had stood longer in the second case than in the first, and the element of time proves to be an important factor in the escape of gas from coal.

However, only the first portion is to be taken as representing the gas liberated during the crushing under full atmospheric pressure. An estimate of the total volume of gas obtained from the crusher on the basis of the analysis of the first portion gave the first two columns of the following table. A comparison of these figures with those in the last two columns, obtained by combining the volumes of the two portions analyzed separately, may help to show how much gas may be attributed to the reduced pressure.

Relations to the coal by volume of gases removed after crushing coal sample 3 in air.

[Tabular Matter Omitted]

The confirmatory tests were made with other samples of coal from Monongah mine No. 6. Sample 4 was collected December 16, 1907, from the face of the east returning air way, and crushed March 10, 1908. Sample 5 was collected December 13, 1907, from the face of the II manway, and crushed March 18, 1908. Each of these

samples was crushed in air under barometric pressure, and the gas removed in two portions. For each sample the total volume of methane was calculated for both portions of gas, on the basis of the analysis of the first portion, which came over with the first stroke of the pump. At least this calculated amount of methane must have come off without the aid of reduced pressure. Expressed in terms of the volume of coal which was crushed down to 30-mesh, the amount for sample 4 was 0.27, and for sample 5, 0.79. The volume of methane actually obtained for the two portions was, in the same terms, 0.41 for sample 4 and 0.86 for sample 5.

In the test of sample 5 the difference between the total volume of methane actually obtained and the calculated volume which must certainly have been liberated from the coal under full barometric pressure is small. Moreover, only a portion of this small difference can be attributed to the effect of reduced pressure, as other factors, such as slow diffusion and the greater interval of time, have helped to cause this difference.

For a series of systematic experiments to show the amount of methane which is liberated from the same coal under various conditions, the can of coal which was collected from the face of the H manway in Monongah mine No. 6 was selected (sample 5). The results of crushing lumps of this coal are as follows, the several tests being set forth in numbered paragraphs, with the volume of coal crushed to 30-mesh and to 10-mesh:

1. Coal was crushed in a vacuum, but so much water vapor was given off and drawn past the calcium chloride drying tube into the pump that in order to draw over all the gas it was necessary to keep the pump going for nearly one hour. Hence the time factor enters here. Ratio, by volume, of methane to 30-mesh coal, 0.88; to 10-mesh coal, 0.33.

2. Coal crushed in a vacuum and the gas immediately pumped off. Then a full atmosphere of carbon dioxide was run in and pumped out, bringing with it the last traces of methane. Two separate trials were made, giving ratios of 0.89 and 0.83, respectively, to 30-mesh coal, and 0.38 and 0.34 to 10-mesh coal.

3. Coal was crushed in a vacuum, but phosphorus pentoxide was used as a drying agent instead of calcium chloride. Ratio of methane to 30-mesh coal, 0.84; to 10-mesh, 0.33. After pumping out this gas and removing it for analysis, an atmosphere of carbon dioxide was run in as rapidly as the apparatus could be manipulated, and then pumped out again quickly, and the gas collected over a 30 per cent solution of potassium hydroxide. More methane came over, some, and perhaps most, of which is to be explained by the time consumed in the carbon dioxide treatment. The amount was 0.14 of the volume of 30-mesh coal, and 0.05 of the 10-mesh coal.

4. Coal crushed in air under barometric pressure. This test has been described on page 21 (sample 5). The amount of methane was 0.86 of the 30-mesh coal and 0.41 of the 10-mesh.

5. Coal crushed under barometric pressure in an atmosphere of pure carbon dioxide. Amount of methane, 0.91 of the 30-mesh coal, 0.44 of the 10-mesh.

Tests 6 and 7 were made to determine the influence of the length of time during which the coal is allowed to stand after crushing, upon the quantity of gas given off.

6. Coal crushed in a vacuum and allowed to stand 3½ hours with occasional pumping. Then the

apparatus was filled with carbon dioxide and pumped out again. Total duration of the experiment, 4 hours; considerably more gas was thus obtained than when the process was completed in less than 1 hour. Analyzed in four separate portions. The total methane was 1.38 times the volume of 30-mesh coal, and 0.57 of the 10-mesh.

7. Coal crushed in a vacuum. Pumping kept up for 1 hour; then, after a short time, 30 cubic centimeters of hydrogen were let in and soon pumped out. After 1½ hours an atmosphere of carbon dioxide was run in and pumped out again. Duration of experiment, 4 hours. Analyzed in three portions. Total methane, 1.39 times the volume of 30-mesh coal, and 0.53 of the 10-mesh.

These last two experiments, in which the totals include all the methane which escaped from the coal during four hours after the process of crushing, show that the gas does not all escape from the coal within the first few minutes after the coal is shattered, and that to obtain comparative results it is necessary that the time consumed during the process of removing the gas after the coal has been crushed be approximately the same in all tests. In the last test the gases pumped off during the first hour, those brought over by the hydrogen, and those which came with the carbon dioxide, were collected and analyzed separately, but nothing of significance was developed except, perhaps, the fact that the hydrogen treatment yielded somewhat less methane than had been anticipated.

These experiments, taken as a whole, appear to indicate that, in respect to the volume of methane obtained from the coal, it makes little difference whether the coal is crushed in a complete vacuum, or under the full barometric pressure, in an atmosphere either of air or of carbon dioxide, provided the gas in each case is quickly pumped out of the crushing apparatus. Gas continues to

escape from the crushed coal at a rather rapid rate for some time after it has been crushed, but this feature will be considered elsewhere.

The quantity of gas immediately liberated from the coal when it is broken up is thus largely independent of the outside pressure. Such gas, therefore, can not be supposed to have come directly from a state of occlusion, for, without an appreciable change either of temperature or pressure, occluded gas should not be given off in this way, even from finely divided coal. Nor can it come immediately from chemical decomposition of the nongaseous constituents of the coal. It must, instead, have been already stored within the mass of the coal as free gas, mechanically imprisoned in numerous pores, cavities, and crevices, from which much of it is immediately released as soon as the confining walls are shattered in the process of crushing, and the pores and cavities opened to the surface. Necessarily, in the process of crushing to this state of fineness, only a portion of the gas-holding pores are so opened as to enable the inclosed gas to escape at once. In many others, the shattering makes it possible for the gas to escape by slow diffusion, where before it was securely held. Hence an abnormally rapid escape of gas follows for a short period of time after the coal has been crushed.

However, it is not impossible that in those tests in which the coal was crushed in a vacuum or practical vacuum, the reduced pressure, acting on the fresh surfaces of the crushed coal, might have caused the escape of some truly occluded gas. If such gas escapes from the coal, it would be likely to come largely from that portion which was most finely pulverized. (See p. 17.) But quantitatively this occluded gas can not play a very important part in the gas liberated by crushing the coal, as its liberation is dependent on a reduction of pressure, and these experiments indicate that, in the volume of gas given off, it makes little difference whether the coal is crushed under

the full barometric pressure or in a complete vacuum. Thus, while there is a possibility, and even a probability, that some of the gas does come from a state of occlusion, it seems more plausible to regard the main bulk of the gas escaping from coal during the process of crushing, and an abnormal rate just after being crushed, as being cavity gas, whose escape is facilitated by the shattering which the crushed coal fragments have received. The fact that the presence of oxygen, nitrogen, hydrogen, or carbon dioxide in the crusher has little influence on the amount of methane given off during the crushing, and for a short length of time afterwards, is in harmony with the theory that this gas escapes largely from mechanical bonds.

GASES FROM COAL BOTTLED IN A VACUUM.

VACUUM BOTTLES.

The experiments with the coal crusher have shown how much gas can be liberated from these coals by crushing them to a certain degree of fineness and opening up many of the gas-holding pores. But this process does not remove all the gas, nor is it the only way to extract the gas from coal without the use of heat. To get the gas which slowly escapes from coal, different samples of coal were stored in vacuum bottles, from which the gas evolved was pumped out from time to time. Each of these bottles had a capacity of 500 cubic centimeters and was fitted with a one-holed rubber stopper containing a short delivery tube. Over the free end of the delivery tube was slipped a short piece of heavy antimony rubber pressure tubing, which serve to make the connection with the mercury pump. A strong screw clamp on the rubber tubing closed the way to the bottle. The stopper and rubber connections were all coated with paraffin to prevent leakage of air. When the air from the bottle had been completely exhausted, the clamp upon the rubber tube was tightly screwed, the rubber tube disconnected from the pump,

and a plug of glass rodding quickly run into the rubber tube as far as the screw clamp would permit. Rendered tight by paraffin the bottle was submerged in a jar of water until the time came to remove the gas. At any time desired the bottle could be connected with the mercury pump and the gas which had accumulated removed for analysis, after which the bottle was again submerged in the water jar.

VOLUME OF GAS.

The volume of the gas extracted from coal by allowing it to remain in an essential vacuum for a period of time was somewhat variable and depended on the sample of coal, the interval of time between its removal from the coal fragments, and the duration of the experiment. The finer the coal the more rapidly and completely was the gas liberated in a given period of time. At the end of six months gas was still accumulating steadily in those bottles which contained lump coal, and it was only in those containing crushed coal that the escape of gas had nearly ceased. The volume of gas from the crushed coal ranged from 0.9 to 2.3 times that of the coal from which it came. The lump coal yielded gas to the extent of 0.5 to 0.9 of its own volume during half a year at low pressure. Because of the pressure of other laboratory experiments, and the time required for the inspection of the Darr mine shortly after the material was collected at Monongah, more than a month elapsed between the collection of the coal samples and the bottling of them in a vacuum. These figures, therefore, do not represent all the methane given up by the coal since its removal from the seam, for a certain quantity of the gas may be supposed to have escaped while the coal was in the collecting cans.

To obtain data on the volume of gas lost during the first month after the removal of the coal from the seam, samples of fresh coal were collected in the usual cans, which were at once hermetically sealed with a thick coat-

ing of paraffin, before leaving the coal face. When opened in the laboratory about a week later, a determination of the gas in the cans was made, after which some of the coal was immediately placed in the vacuum bottles. In this way all the gas escaping from the coal after the sample was mined at the working face was determined. A specimen of bituminous coal in the form of lumps from the Mansfield mine at Carnegie, Pa., gave off 0.55 of its volume of gas, exclusive of nitrogen, during seven days in the collecting can and thirty days in the vacuum bottle. Analyses made at intervals during this length of time indicated that gas was freed much more rapidly during the first few days after collecting than later. But a similar experiment with gassy anthracite coal showed only a slight slackening in the rate of methane escape, and this change in the rate was almost uniformly distributed throughout the period of observation.

CHARACTER OF GAS.

The coal thus bottled in a vacuum was kept under observation for a period of half a year, during which time the bottles were connected with the mercury pump at stated intervals and the gas which had accumulated was removed for analysis. Thus not only was the rate at which the gas escaped from the coal discovered, but the character of the gas evolved throughout this length of time was determined. However, as the principal object of the experiments in which these vacuum bottles were employed was to determine the volume of methane escaping from the coal during a given interval of time, less care was given to the determination of the minor constituents, especially carbon monoxide and the ethylene series. In some tests the absorption of the olefins with fuming sulphuric acid, or bromine water, was omitted, and the gases of this series were removed, together with carbon monoxide, by cuprous chloride. Also, the leakage of small quantities of air into the vacuum bottles was not prejudicial to the chief purpose of the experiments, for

the volume of methane was in no way affected. Although these analyses are subject to these limitations, they yet serve to indicate pretty closely the general character of the gas which escaped from the coal during the period of half a year under reduced pressure. Four of these sets of analyses of the gas from coals are given in the table following.

Analyses of gases escaping from small lump coal bottled in a vacuum, with relation to the coal by volume

[Tabular Matter Omitted]

The analyses of the gas from the other samples of Carboniferous coal which were subjected to this same treatment show similar results.[a] The most noteworthy change in the nature of the gas escaping from the coal during the period of observation was the steady decrease in the proportion of nitrogen and the corresponding increase in the percentage of methane. Much of the nitrogen that appeared in the portion of gas removed from the bottles at the end of the first three weeks doubtless came from air which adhered to the coal or was absorbed by its mass, and was not given off immediately when the vacuum was produced. As the oxygen which coal absorbs enters rapidly into chemical union with the substance of the coal, the latter respires chiefly nitrogen (with some carbon dioxide) in place of the air taken in. The influence of the nitrogen from the air is naturally most felt during the early part of the sojourn of the coal in the vacuum bottles, as this nitrogen is largely held by the surface layers or in the more prominent crevices and lines of fracture. It therefore escapes from the coal more readily than the gas originating in the coal, which is distributed throughout its mass, but most abundantly in

[a] The Cretaceous coal from New Mexico, however, behaved differently (giving 30 to 40 per cent carbon dioxide and only 4 per cent methane), but that is outside the field of this report.

the interior of the fragments, from which escape is slow and difficult. As this extraneous nitrogen was removed, the percentage of the methane rose proportionately.

Methane was quantitatively by far the most important gas which escaped from the bottled coal. After the extraneous nitrogen had been removed, it ran in some tests as high as 98 per cent of all the gas coming from the coal. More commonly, however, it constituted from 80 to 95 per cent of the gas liberated. Methane reached its highest percentage in the gas from anthracite coal, which yielded only small proportions of the other constituents, carbon dioxide and nitrogen.

In addition to methane, at least one other higher member of the paraffin series was found. In nearly every analysis the explosion of the residual gas with oxygen, after the removal of the absorbable gases, produced carbon dioxide in slight excess over what would have resulted from the combustion of methane alone. Calculations show that the excess of carbon dioxide noted can be explained by the presence of ethane in proportions of a trace to 4 parts of C_2H_6 to 100 parts of CH_4. Other higher paraffins may be present in small quantities, but the computations are made on the basis of ethane alone, as $C_3H_8+CH_4 = 2C_2H_6$. So far as the tests have been carried, the bituminous coal has yielded more ethane than the anthracite (one sample only). In fact, in several tests the explosion of anthracite gas, instead of indicating higher paraffins, suggested the presence of a small amount of hydrogen.

Carbon dioxide was found to be a more variable constituent of the gas, depending on the nature of the coal from which it came. The various experiments with the Monongah coal show that in most of the samples it amounted to 1 to 3 per cent of the gas which accumulated in the bottles. In the bituminous coal from the Mansfield mine at Carnegie, Pa., carbonic anhydride became much more important, reaching 13 per cent of the

total gas given off. But on the other hand, careful analyses made over mercury failed to detect any carbon dioxide in two out of the four portions of gas from the anthracite coal of Nanticoke, while the analyses of the other two portions revealed the presence of only small quantities of this gas. Although the proportion of methane steadily increased as the experiment progressed, in general the proportion of carbon dioxide fluctuated during the period of observation.

The volume of nitrogen in the bottles fell rapidly during the progress of these experiments. Apparently much of the nitrogen which was obtained from coal by this and other methods, especially that portion of the gas which came off most readily, is not to be regarded as gas held by the coal while in the undisturbed strata, but as nitrogen absorbed by the coal after it became exposed to the air in the mining operations. Some of it was derived from air adhering to the coal and tubes in spite of the effort of the mercury pump to remove it. The leakage of air into the bottles could take place only while they were out of the water jar and connected with the pump. Hence, most of whatever inleaking air there may have been was quickly pumped over into the gas receiver with the rest of the gas, and was determined in the analysis on the basis of the amount of oxygen found. Only such air as could leak into the bottle, between the closing of the screw clamp and the immersion of the bottle in the water jar after sealing the rubber-tube connection with glass plug and paraffin coating, could remain in the bottle with the coal during the interval between tests. Absorption of oxygen from such air by the coal would leave an excess of nitrogen in the gas. But as less than one minute elapsed between the closing of the screw clamp and the immersion of the bottle, the amount of leakage was reduced to a small figure. The excess of nitrogen in the analyses of the portions of gas taken at the end of the half-year period indicated that the coal did contain nitrogen as a truly original gas. This may have come originally in part from air buried with the accumulated

vegetable matter and in part from the decomposition of nitrogenous compounds in the organic matter whose metamorphism produced the coal.

The minor constituents of the gas from coal were carbon monoxide and one or more members of the olefin series, most probably ethylene.

The above figures represent the character of the gas escaping from lumps of coal averaging somewhat less than a cubic inch in size. The evolution of gas had in no case ceased at the end of the six-months period. Instead, gas was still steadily accumulating in the bottles, though at a diminishing rate. The composition of the last portion of the gas which would eventually escape, if the experiment were carried on for a much longer period, can only be inferred from these experiments with the lump coal. However, from the studies on the finely crushed coal, from which the gas escaped much more rapidly and completely in a given length of time than from the coarser fragments used in the above tests, more can be learned on this question. Two representative experiments with coal crushed in the rock crusher so as to pass through a 10-mesh sieve, and then bottled in a vacuum, may be selected to illustrate the composition of the gas which came from the coal after the main bulk of the free gas had been liberated and the outflow had nearly ceased.

Analysis of gases escaping from crushed coal bottled in a vacuum, with relation to the coal by volume.[a]

[Tabular Matter Omitted]

According to the foregoing table the relative proportion of both carbon dioxide and carbon monoxide in-

[a] Coal from the face of H manway in Monongah mine No. 6, crushed so as to pass through a 10-mesh sieve, and then quickly placed in the vacuum bottle. The rate of methane liberation is shown by curve 7 of fig. 1.

creased greatly during the last weeks of each experiment, chiefly in consequence of the rapid slackening in the output of methane. This gas, because it diffuses and transpires at more rapid rates than the other gases mentioned, escaped from the coal sooner than the less active molecules, and hence the stored-up supply of free methane in the coal was more quickly depleted than that of carbon dioxide. Thus, on theoretical grounds, the coal may be expected to give off carbon dioxide for a longer period than methane. But these tables not only indicate an increase in the relative proportion of carbon dioxide and carbon monoxide during the latter part of the experiment, but they appear to show also an absolute increase in the volume of the oxides of carbon evolved per unit of time. During the first few weeks after the coal was bottled in a vacuum there was a reduction in the rate of outflow of all the gases, but during the last ten weeks of the last-year period the evolution of the oxides of carbon apparently proceeded at an accelerated rate. This feature was most conspicuous in experiments E and F, but the same phenomenon was also shown, though in a less striking manner, in the results of the two other similar series of analyses which furnished the data for curves 4 and 8 of figure 1.

The experiments with the rock crusher indicate that a large part of the free gas held by coal is mechanically imprisoned, under pressure, within the pores, interstices, and lines of fracture of the coal. Such gas is released immediately when the coal is pulverized and many of the gas-holding cavities are broken open. Many of the pores charged with gas are not opened by the crushing process, so that much cavity gas still remains in the crushed coal. Of the gas exhaled when the coal is placed in a vacuum, it seems safe to assign the bulk of the methane, carbon dioxide, and other gases which escape from the coal, rapidly at first, but at a progressively declining rate, to this mode of occurrence. The gases under pressure in the interstices of the coal are supposed to reach the surface by diffusion, or more strictly, transpiration, and to

escape until in time the gas thus mechanically held has bled itself out. The curves showing the rate of escape of methane support this view in regard to that gas. But the behavior of carbon dioxide and carbon monoxide in this respect appears to be different. The declining volumes of these gases during the first few weeks are natural enough, as the cavity gas comes off in greatest volume immediately after the coal is crushed. But reasons for the apparently increasingly volumes toward the end of the experiments are less easily found. Possibly the increment of carbon dioxide and carbon monoxide may come from a state of occlusion. Charcoal, which is like coal, is known to absorb the oxides of carbon in much greater volume than hydrogen [a] and probably also in greater volume than methane, though the figures for the latter are not at hand. The presumption, therefore, is that of the coal gases the oxides of carbon are likely to be held in greatest volume as occluded gas. But why such gas, even if occluded, should be liberated most rapidly after so long an interval is not apparent at the present time. Perhaps the explanation is to be found in chemical changes. For the present, however, the cause of this phenomenon must be left open. Further experimentation, to determine how generally the rule is true of different coals, is necessary before more is made of this point.

COMPARISON WITH MINE GASES

To make a comparison between the composition of the gas which escapes from the bottled coal in the laboratory, and that which issues from the rock strata, a few analyses of feeder gas from the mines may be introduced:

Analyses of feeder gas.

[Tabular Matter Omitted]

The presence of a higher member of the methane series, probably ethane, was noted in Nos. 1, 3, and 4, but the

[a] Moissan, Chimie minérale, vol. 2, pp. 251-253.

paraffins have here been computed as so much methane. In No. 5, after the removal of the hydrogen by palladium, the explosion indicated only methane.

A comparison of the foregoing table with that on page 26, after the proper allowance is made for air and nitrogen absorbed from the air by the coal used in the laboratory experiments, fails to show any significant difference between the feeder gas encountered in the mines and the gas extracted from lumps of coal in the laboratory by means of a vacuum. But a comparison with the table on page 29 shows that, while the feeder gas bears a close resemblance to the gas which is obtained from the finely crushed coal during the first few weeks under reduced pressure, it is quite different from the gas which is finally exhaled from the fine coal after it has stood some months and has lost the bulk of its free gas. The feeder gas does not contain the high percentages of carbon dioxide and carbon monoxide which characterize the last gas to escape from the fine coal. Feeder gas therefore represents that portion of the gas which is first to escape from the coal and which comes out most readily. It would seem to be that portion of the gas which, having been mechanically held at the outset in the interstitial spaces throughout the mass of the coal stratum, has subsequently escaped from the scattered pores in the coal and has accumulated along more or less connected lines of fracture, or other places of weakness or increased porosity. Traveling along these, it now issues into the mine workings from distinct orifices, cracks, or localized portions of the coal bed, at a more rapid rate and in greater volume than it is elsewhere exhaled from the solid coal.

Necessarily the issuance of gas in the form of feeders, under pressure, must die out long before the steady exhalation from the body of the coal, though the same lines of fracture continue to serve as paths of discharge for the gases slowly but steadily gathering in the porous reservoirs back in the coal. And to judge from the slowness with which even small lumps of coal manifest a change in the character of the gas transpiring from them, even

when favored by a reduction of pressure, it would seem that a very much longer period of time would be required to produce the change in composition which the behavior of the finely crushed coal suggests will ultimately occur in the gas freed from the solid coal.

But in the case of pillars and other coal surfaces long exposed to the the weathering action of the mine air, there enters another factor which is absent in the vacuum-bottle experiments—that is, the steady oxidation of the coal by the oxygen of the air. Experiments on coal bottled in air, under ordinary barometric pressure, show that oxygen is rapidly absorbed by the coal until, after a few days, there remains often only 1 or 2 per cent of oxygen in the free gas in the bottle. At the same time a certain proportion of the oxygen uniting with the coal comes off again as carbon dioxide, but this, at least during the short time of the experiment, amounts to only a small part of the oxygen entering the coal. Perhaps with an abundance of air and a much longer period of time, so as to allow the coal to absorb oxygen to its full capacity, a much larger proportion of it might eventually reappear from the saturated hydrocarbon compounds, as carbon dioxide.

The feeder gas originates back in the coal seam, away from the influence of the air, and hence it does not contain carbon dioxide from the direct oxidation of the coal. But the exposed coal surface must produce carbon dioxide in this way and thus supply the mine air with carbonic acid, which, though coming from the coal, is largely independent of the free gas content of the coal. This property appears to vary in different coals. The gassiness of a certain coal is not necessarily an index to the volume of carbon dioxide which may be developed from it as a contribution to the mine air. A few analyses made in Germany of the air from unexploded mines indicate a higher proportion of carbon dioxide, in comparison with methane, than is found in the feeder gas, suggesting that the oxidation of the coal may be a more prolific source of

the carbon dioxide encountered in the mines than the outflow of the free gas stored within the coal.

RATE OF ESCAPE

The samples of coal were kept in the vacuum bottles for twenty-six weeks, or just half a year. At stated intervals during this time the gas which had accumulated was pumped out and analyzed. As methane was by far most abundant gas thus obtained, as well as the most important from the standpoint of this investigation, the volumes of that gas given off per unit volume of coal were taken as the standard. Curves were plotted, as in figure 1, to show the rate of escape of this gas from the coal, the ordinates of the graph representing the relative volumes of methane, and the abscissas expressing the progress of time in weeks.

Descriptions of the samples of coal and the conditions from which the several curves were plotted follow:

Curve. 1. Methane from coal collected from the face of the fourth right entry, off the F face heading, in mine No. 6, at Monongah, December 13, 1907; bottled in vacuum January 23, 1908.

Curve 2. Same coal as No. 1. Crushed in vacuum on January 27 by means of coal crusher, and then placed in the vacuum bottle.

Curve 3. Methane from coal collected from room 3 on third right off second north heading, in mine No. 8, Monongah, December 12, 1907; bottled in vacuum January 23, 1908.

Curve 4. Same coal as No. 3. Crushed in vacuum in coal crusher January 28, and then placed in the vacuum bottle. Coal passed through 30-mesh sieve. Curve 5 Coal from the face of the east return air way in mine No. 8, Monongah. Collected December 17, 1907; bottled in vacuum February 10, 1908.

Curve 6. Coal from face of right main, Naomi mine. This is the most gassy point seen in the mine. Collected December 14, 1907; bottled February 11, 1908.

Curve 7. Coal from face of H manway, mine No. 6, Monongah. Collected December 13, 1907; crushed in vacuum March 17, 1908, and immediately placed in vacuum bottle.

Curve 8. Same coal as No. 7. Crushed in air under full barometric pressure on March 18, 1908, and immediately placed in vacuum bottle.

Curves 1, 3, 5, and 6 show the escape of methane from lumps of coal averaging approximately the size of a marble. Curves 2, 4, 7, and 8 indicate the volume of gas which escaped from coal crushed so that all of it would pass through a 10-mesh sieve, a considerable part of it being necessarily much more finely reduced than this.

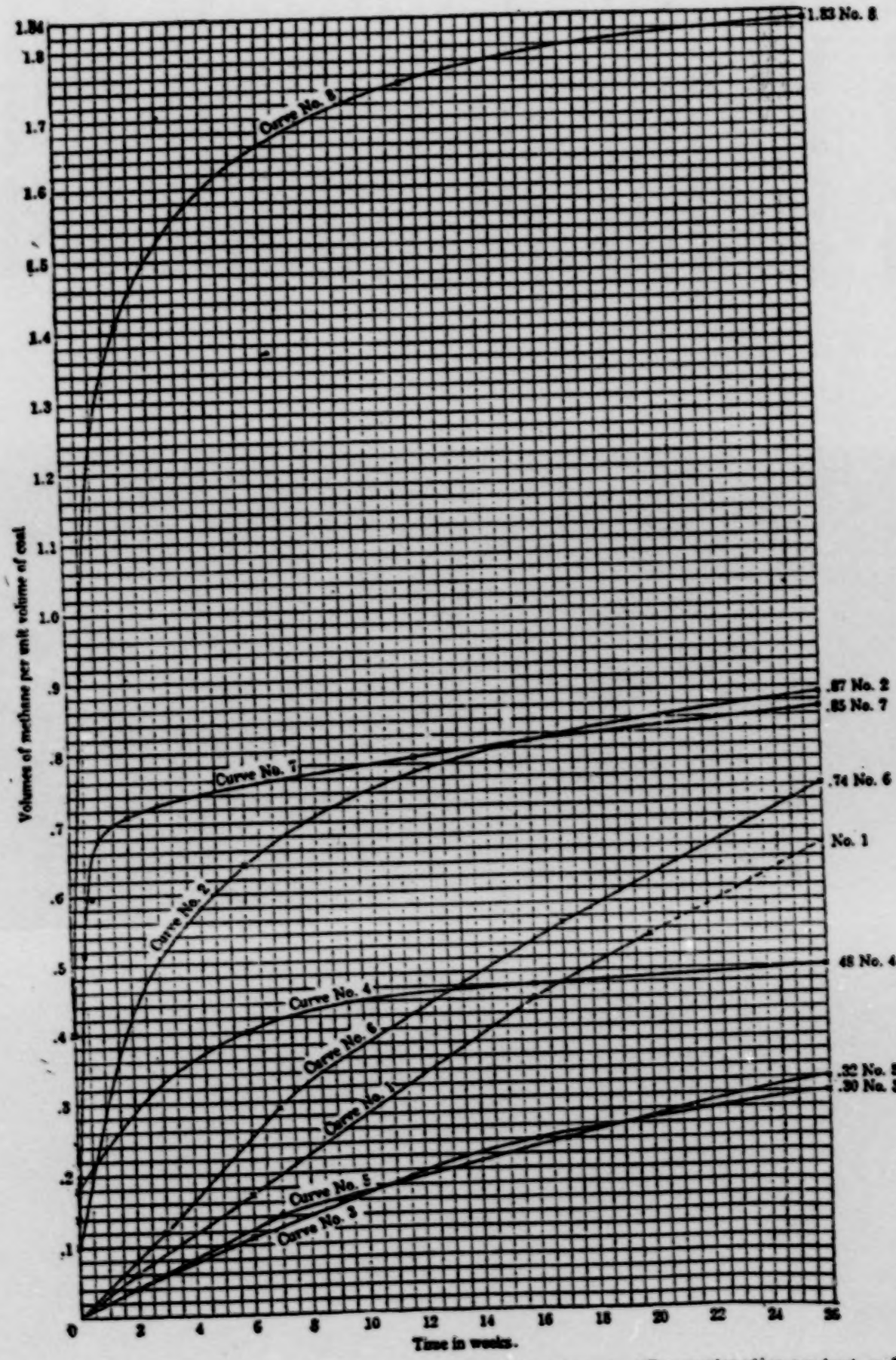

FIGURE 1.—Diagram showing rates of escape of methane from coal. (For explanation see text, p. 33.)

BEST AVAILABLE COPY

The volumes of methane liberated during the process of crushing are also included in these curves. Hence curves for the crushed coal instead of commencing at the zero point start at points on the vertical axis corresponding to the volume of methane lost during the process of crushing.

The four curves representing the lump coal show that the escape of methane from fragments of coal, even in a vacuum, takes place slowly and steadily and must in some cases continue for a very long period of time. Curve 1 is nearly a straight line, showing that the evolution of methane was nearly as rapid at the end of twenty weeks as when the coal was first placed in the vacuum. In the other three experiments the rate of escape declined more rapidly.

The relation between the size of the coal fragments and the rate of gas escape is strikingly shown by comparing the curves obtained from the crushed coals with those representing the same coals in lumps. Curves 1 and 2 were parallel experiments with the same coal, as were also curves 3 and 4. The finely-crushed coals gave out methane at a very rapid rate for a short time after being bottled, but the rate soon rapidly declined. In the experiments represented by curves 7 and 8 the escape was exceedingly rapid during the first week after the crushing, but had greatly slackened before the end of the second week. Bottles 2 and 4 were not opened until the end of the sixth week, so that these two curves are not so sharply bent.

It is clear from these experiments that the gas escapes more readily, and at first in greater volume, from the fine coal than from the coarser lumps, but that the supply of free gas held by the fine coal is more quickly depleted, while the loss from the lump coal is more uniform. After a time, therefore, the coarse coal gives off gas more rapidly than the fine. The graph shows that the curves for the same sample of coal approach each other and will

apparently come together in time, probably at a point where the gas supply of each has been practically exhausted. It seems probable, therefore, that the size of the coal, whether finely divided or in the form of coarse lumps, has little influence on the total amount of methane evolved in a sufficiently long period of time, but that it makes a very great difference in the rate at which the gas is given off. The phenomenon appears to be chiefly one involving the quantity of gas stored within the coal which can escape, and not one of gas generation during the interval of time.

Some of the results of these experiments on the rate of escape of gas from Monongah coal may be summed up in the following generalizations:

1. Reduction of pressure removes the gases from coal slowly—a matter of weeks and months.

2. Finely powdered, fresh coal gives off more methane during six months in a vacuum than the same amount of lump coal subjected to the same conditions. But presumably during a much longer period of time approximately the same volume of gas should be expected to come off from either type of coal.

3. Reduction of pressure, acting for only a few hours or even a few days, is far less effective in extracting the entrapped gas than crushing the coal, either in a vacuum or under barometric pressure.

4. Crushing coal to a certain degree of fineness yields approximately the same volume of methane whether the operation is performed in a vacuum or in an atmosphere of air or carbon dioxide.

5. Crushing the coal to the degree of fineness of which the crusher is capable removes only a minor proportion of the free gas stored within the coal. For Monongah coal already crushed, either in vacuum or under full atmospheric pressure, will yield more methane during

the next two weeks in a vacuum than was liberated during a process of crushing.

PRACTICAL SIGNIFICANCE OF RATE.

The escape of methane, which takes place slowly and steadily, even from small lump coal, and at a rate that is much influenced by the size of the coal, must continue very steadily for long periods of time from the solid coal in the mines. This means that throughout every portion of a mine, in the old workings as well as the new except in the portion of the seam near the surface from which the gas has been slowly escaping during long geologic ages), a steady outbreathing of methane gas is to be expected. This may be independent of recognizable "feeders" and "blowers" and may come from the massive coal, as well as from distinct cracks and fissures leading back to storage reservoirs. But because this gas escapes as slowly as it does steadily, it does not often become dangerous in mines where the ventilation is good; but old, abandoned workings, cut off from the rest of the mine and from the ventilation, soon fill with methane from this continual exhalation of gas.

A much greater danger lies in those more rapid outbursts of fire damp which unexpectedly flow into the new workings when a strong blower or reservoir of gas is encountered. Necessarily the quantity of gas suddenly forced into the workings must vary within extremely wide limits, depending on the nature and extent of what may, for convenience, be termed the storage reservoir. These so-called reservoirs of gas are, in reality, porous portions of the coal seam or adjacent strata, or a series of fissures, in which the gas has accumulated and is now stored, at many places under very great pressure. When a crack or fissure leading back to a region of stored gas is encountered in mining operations, an outflow of gas into the working results. Sudden falls of rock from the roof often open avenues of escape for pent-up gas. When lines of

communication with extensive reservoirs of stored gas are opened, large quantities of fire damp may flow into a portion of the mine in a short time and thus render the air in this part of the mine explosive. These lines of communication may be opened either in the ordinary mining operations or because of the formation of new lines of fracture accompanying the natural deformation movements of the strata. Settling of the overhead beds, together with a general redistribution of the strains caused by the removal of the coal, is likely to open new sets of fissures and seal old ones. Hence there may be periods of more gas and periods of less gas, depending on the local movements of the strata and the effect of such movements, by opening or closing fissures, on the facility with which the pent-up gases can find lines of egress. No appeal, however, is here made to seismic or volcanic disturbances in other parts of the world, whose influence on the local conditions must be trivial.

From these experiments it has seemed safe to conclude that the solid coal in the seam must continue to supply methane for long periods of time. This means that as the supply of gas collected in reservoirs is reduced by escape into the mine, the adjacent coal has a tendency to yield gas to replace that which is lost, until (in case the avenue of escape is cut off by movements of the strata or other causes) a state of approximate equilibrium is established between the gas distributed throughout the mass of the coal itself and that accumulating in the so-called reservoirs. If a reservoir of gas were tapped by boring and the gas removed, the reservoir would, in the course of time, be likely to become recharged, partly at least, with more gas supplied by the adjacent coal, provided the avenue of escape became closed. Just how rapidly a depleted reservoir might be resupplied with gas, and what bearing this factor has on practical mining, must be left an open question for the present.

EFFECT OF BAROMETRIC CHANGES.

When the lumps of coal were placed in the vacuum bottles and the air was exhausted by means of the mercury pump, it was found that the reduction of the pressure to a fraction of a millimeter caused the immediate escape of only a small quantity of methane. The exhaust air from the bottles of Monongah coal contained methane in volumes ranging up to 0.002 of the volume of the coal. Lumps of coal from the Naomi mine and the Mansfield mine at Carnegie, Pa., added similarly small volumes of methane to the exhaust air. Three samples of coal from the mine at Cardiff, Ill., gave only traces of methane, but a fourth, from a gassy portion of the mine, gave off 0.003 of its volume of methane. A bottle of anthracite coal from No. 1 north shaft of the Susquehanna Coal Company at Nanticoke, Pa., gave off methane to the extent of 0.03 of the volume of the coal while the air was being pumped out of the bottle. The time required to remove the air from these bottles was about twenty minutes. Thus a sudden drop of 740 to 750 millimeters in pressure within twenty minutes does not bring out a very large volume of gas. Experiments already described have shown that time is required to bring out the gas, even in a vacuum.

To discover how much more gas is given off from coal under low pressure than under the full barometric pressure, 20 pieces of bituminous coal from the Mansfield mine at Carnegie, Pa., were placed in a vacuum bottle and the air exhausted. At the same time 21 chunks of similar size, taken from the same collecting can, were placed in a bottle filled with air. The two bottles were then submerged side by side in a water jar. At the end of ten days the gas which had accumulated in the interval was pumped out and analyzed. The coal which had been bottled in a vacuum was found to have given up 0.25 of its volume of methane, while methane amounting to 0.14 of the volume of the coal had accumulated in the bottle

that had been filled with air. A similar experiment with two bottles of anthracite coal from Nanticoke, Pa., showed, after an interval of one week, exactly the same relative volume of methane in each bottle—1.07 times the volume of the coal. As in each experiment the volume of methane liberated was greater than the volume of oxygen which the coal absorbed from the air, the final pressure in the air-filled bottles was greater than the barometric pressure.

Low pressure aided the escape of gas from the bituminous coal, but it appears to have had little influence on the liberation of gas from this sample of anthracite coal. That identical volumes of methane should have escaped from the anthracite coal under such widely different pressures is perhaps to be regarded as largely a coincidence, for the distribution of gas is not uniform throughout the coal; but with about 20 fragments of the coal in each bottle, the gas content of the coal in one bottle should not differ greatly from that in the other. It is to be noted that, while the total pressure in each of these air experiments was very different from that in the parallel vacuum experiment, the partial pressure due to methane alone started at zero in each bottle and at the conclusion of the experiment with the anthracite coal had become as great in one bottle as in the other. In considering the influence of barometric fluctuations on the volume of gas exhaled by the coal in the mines, however, it is the total gas pressure which is of significance, rather than the partial pressure due to methane.

It would seem therefore that even the greatest fluctuations of the barometer, which do not exceed 40 millimeters, can not have very great influence on the volume of gas escaping from the interstices of the coal itself. But in the case of feeders and blowers, in which the gas escapes for the most part directly from accumulations stored within more or less connected systems of fissures and zones of fracture, instead of from minute pores in the coal, the

effect of the diminution of pressure probably is more marked. This should be particularly true wherever the stored gas is under only a moderate pressure and the pathway of escape into the mine workings is readily followed; the strong blowers coming from the reservoirs far back in the coal, where the gas is held under high pressure and communication with the coal surface is more difficult, are necessarily much less affected by the relatively slight barometric changes.

Heise and Herbst bring out the point that, although frequent measurements have shown that the gas stored up in the fresh, undisturbed coal often is under pressure amounting to several atmospheres, these high pressures are obtained only by boring several meters back into the coal; and that close to the coal face the gas is under a pressure but slightly in excess of the barometric pressure.[a] Blower gas, in that portion of its course which is near the orifice, is under only a slight pressure, so that an increase in the barometric pressure adds resistance to its outflow, causing it to slacken, whereas with a falling barometer the outflow of gas must become more active. In this way the common observation that the outflow of gas from blowers increases with a falling barometer and slackens perceptibly with a rising barometer is shown to be entirely consistent with the high gas pressures that have been found to exist in the undisturbed coal some distance from the exposed face.

The influence of barometric changes on the outflow of air and gas into the active workings from old abandoned entries which are not completely walled off from the rest of the mine is well known and does not fall within the scope of this discussion.

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[a] Heise and Herbst, Bergbaukunde, vol. 1, 1908, pp. 458-461.

GASES OBTAINED BY HEATING COAL.

Meyer,[b] Thomas,[c] Bedson,[d] Trobridge,[e] and other investigators have extracted gases from coal with the aid of heat, by warming the coal generally up to the boiling point of water, and in some experiments as high as 200° C. In many tests the higher members of the paraffin series, such as ethane, propane, and butane, were obtained in considerable proportions. At least one gas of the olefin series was often present in notable quantities.

The present analyses of feeder gas from the mines and of the gas which slowly escaped from the coal bottled in a vacuum, as well as of that liberated directly by crushing the coal in the rock crusher, do not reveal the presence of any such high proportions of the heavier hydrocarbons. But these gases were all extracted at ordinary temperatures. As the constituents of coal include various hydrocarbon compounds, some of which may be supposed to be partly decomposed or volatilized at even moderate temperature, there comes to mind the suggestion that a portion of the olefins and higher paraffin gases obtained from these European coals, instead of existing within the coal in the free state, may have been produced from chemical decomposition induced by the heat employed. To test this possibility, parallel experiments were undertaken. A can of fresh bituminous coal from the Pittsburg district being selected for this test, one portion of the coal was stored for thirty days in a vacuum bottle; a second portion was pulverized on an anvil so as to pass through a 10-mesh screen, and then quickly placed in a suitable glass tube connected with the mercury pump, and the air re-

[b] Von Meyer, Ernst, Jour. Chem. Soc., vol. 25, 1872, pp. 798-801.

[c] Thomas, J. W., Jour. Chem. Soc., vol. 28, 1875, pp. 793-822, and vol. 30, 1876, pp. 144-152.

[d] Bedson, P. Phillips, and McConnell, W., Trans. Fed. Inst. Min. Eng., vol. 3, 1892, pp. 307-310; vol. 7, 1894, pp. 27-53.

[e] Trobridge, F. G., Jour. Soc. Chem. Ind., vol. 25, 1906, p. 1129.

moved. This tube was then kept for three hours successively at 50° (water bath), 100° (boiling water), 150° (oil bath), and 200° (metal bath). The gas obtained during three hours at each temperature was collected and analyzed. The same experiment was then repeated with anthracite coal from the vicinity of Scranton, Pa. The results, expressed in volume of each gas relative to the volume of the coal as unity, are given in the following tables:

Analyses of gases obtained from coal in a vacuum at different temperatures.

[Tabular Matter Omitted]

The other portions of these two coals were kept in vacuum bottles at low pressures for thirty days. At intervals during this period the gas which had accumulated was pumped out and analyzed, in order to furnish additional data on the rate of methane liberation (see pp. 33-36). The gas was pumped from the bottle containing the bituminous coal at the end of each ten days; from the anthracite at the end of each week, except that the fourth period was extended to nine days to complete the full thirty days.

Of the different portions of the gas analyzed, the last portion in each test furnishes the truest index to the character of the gas given off by the coal when allowed to stand under reduced pressure, as after the removal of several portions of gas the extraneous nitrogen resulting from air still adhering to the coal when bottled, has been largely removed. The gas was still coming off rapidly at the end of the thirty days.

The following table indicates the character of the last portion of the gas obtained from these two vacuum bottles:

Analyses of gases given off by coal during last 10 of 30 days in a vacuum.

[Tabular Matter Omitted]

Ethane was present in the gas from the anthracite coal, if at all, only in small quantities. In two of the four analyses made of the gas from this coal the result of the explosion determinations indicated a small amount of hydrogen instead of higher paraffins. The explosions in the other two analyses pointed to the presence of a small proportion of ethane accompanying the methane.

A comparison of the three tables shows that for these two coals the gas extracted by heating the material up to 200° C. is somewhat, though not radically, different from that which slowly exudes from the coal when bottled for a period at ordinary temperatures. The heat caused the expulsion of such uncombined gas as was ready to escape at ordinary temperatures, and in addition developed some new gas from the nongaseous constituents of the coal. Most conspicuous among these new products were the vapors of hydrocarbons which at ordinary temperatures are normally liquids. Benzene was probably the most prominent of these vapors. The hydrocarbon vapors began to appear in notable quantities at 100° and increased in importance as the temperature was elevated. The volume of ethane also rose slowly with the increase of heat, suggesting that some of this gas did not come from a state of mechanical imprisonment in the pores of the coal, but was produced by chemical action induced by the heat. Gases of the ethylene series remained unimportant, even up to 300°, in the experiments with the anthracite coal.

The high proportions of higher hydrocarbon gases obtained by Meyer, Thomas, and Bedson by heating German and English coals up to 200° were not found in the gas from these two samples of Pennsylvania coal. By heating dust from the Darr mine up to 350°, however,

both olefins and higher paraffins, which at lower temperatures had appeared only in moderate quantities, were made important constituents of the gas evolved. (See tables on pp. 57-58.) Such gases could have come only from chemical action or from a state of true occlusion, for they must inevitably have been liberated in considerable volume at the lower temperatures as well had their liberation been merely a question of escape from the interstices of the coal. Substantiating this view in a measure is the testimony afforded by the vacuum bottles. These experiments show, at least as regards the coals used in these investigations, that the gas slowly coming off from the crushed coal at the end of a period of six months at very low pressures is not notably richer in the higher members of the marsh-gas series than the gas rapidly exhaled at the beginning of the experiments. These higher hydrocarbons do not diffuse and transpire so rapidly as methane, but if they were present in any considerable volume, mechanically held within the pores of the coal, as is the methane, a period of six months would seem sufficient to permit their escape in notable proportions.

SURVEY PUBLICATIONS ON FUEL TESTING AND MINE ACCIDENTS.

The following publications, except those to which a price is affixed, can be obtained free by applying to the Director, Geological Survey, Washington, D. C. The priced publications can be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C.

Bulletin 261. Preliminary report on the operations of the coal-testing plant of the United States Geological Survey at the Lousiana Purchase Exposition, in St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1905. 172 pp. 10 cents.

Professional Paper 48. Report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1906. In three parts. 1,492 pp., 13 pls. $1.50.

Bulletin 290. Preliminary report on the operations of the fuel-testing plant of the United States Geological Survey at St. Louis, Mo., 1905, by J. A. Holmes. 1906. 240 pp. 20 cents.

Bulletin 323. Experimental work conducted in the chemical laboratory of the United States fuel-testing plant at St. Louis, Mo., January 1, 1905, to July 31, 1906, by N. W. Lord. 1907. 49 pp. 10 cents.

Bulletin 325. A study of four hundred steaming tests, made at the fuel-testing plant, St. Louis, Mo., 1904, 1905, and 1906, by L. P. Breckenridge 1907. 196 pp. 20 cents.

Bulletin 332. Report of the United States fuel-testing plant at St. Louis, Mo., January 1, 1906, to June 30, 1907; J. A. Holmes in charge. 1908. 299 pp.

Bulletin 333. Coal-mine accidents, a preliminary report by Clarence Hall and W. O. Snelling. 1907. 21 pp.

Bulletin 334. The burning of coal without smoke in boiler plants; a preliminary report, by D. T. Randall. 1908. 26 pp. 5 cents. (See Bull. 373.)

Bulletin 336. Washing and coking tests of coal and cupola tests of coke, by Richard Moldenke, A. W. Belden, and G. R. Delamater. 1908. 76 pp. 10 cents.

Bulletin 339. The purchase of coal under government and commercial specifications on the basis of its heating value, with analyses of coal delivered under government contracts, by D. T. Randall. 1908. 27 pp. 5 cents.

Bulletin 343. Binders for coal briquets, by J. E. Mills. 1908. 56 pp.

Bulletin 362. Mine sampling and chemical analyses of coals tested at United States fuel-testing plant, Norfolk, Va., in 1907, by J. S. Burrows. 1908. 23 pp. 5 cents.

Bulletin 363. Comparative tests of run-of-mine and briquetted coal on locomotives, including torpedo-boat tests and some foreign specifications for briquetted fuel, by W. F. Goss. 1908. 57 pp., 4 pls.

Bulletin 366. Tests of coal and briquets as fuel for house-heating boilers, by D. T. Randall. 1908. 44 pp., 8 pls.

Bulletin 367. Significance of drafts in steam-boiler practice, by W. T. Ray and Henry Kreisinger. 1909. 61 pp.

Bulletin 368. Washing and coking tests of coal at Denver, Colo., by A. W. Belden, G. R. Delamater, and J. W. Groves. 1909. 54 pp., 2 pls.

Bulletin 369. The prevention of mine explosions, by V. Watteyne, C. Meissner, and A. Desboronugh. 1908. 108 pp.

Bulletin 373. The smokeless combustion of coal in boiler plants, by D. T. Randall and H. W. Weeks. 1909.

60TH CONGRESS
2d Session

DOCUMENT
No. 1554

HOUSE OF REPRESENTATIVES

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, DIRECTOR

BULLETIN 394

PAPERS ON THE

CONSERVATION OF MINERAL RESOURCES

Reprinted From Report of the
National Conservation Commission, February, 1909

WASHINGTON
GOVERNMENT PRINTING OFFICE
1909

CONTENTS

	Page
Introduction	5
Coal fields of the United States, by M. H Campbell and F. W. Parker	7
Estimates of future coal production, by Henry Gannett	27
The petroleum resources of the United States, by D. T. Day	30
Natural-gas resources of the United States, by D. T. Day	51
Peat resources of the United States, exclusive of Alaska, by C. A. Davis	62
Iron ores of the United States, by C. W. Hayes	70
Resources of the United States in gold, silver, copper, lead, and zinc, by Waldernar Lindgren	114
The phosphate deposits of the United States, by F. B. Van Horn	157
Mineral resources of Alaska, by A. H. Brooks	172
Index	209

ILLUSTRATIONS

		Page
PLATE I.	Distribution of coal fields in the United States	6
II.	Distribution of petroleum and gas fields in the United States	30
III.	Illustration of the crowding of wells, Spindle-top field, Texas	33
IV.	Production of petroleum, 1859-1907	38

V.	Decline in production of the New York and Pennsylvania oil fields and its probable rate in the future	44
VI.	Production of gold of the United States and of the principal States and Territories, 1885-1907	120
VII.	Production of gold of the world and of the principal countries, 1800-1906	122
VIII.	Production of silver of the world and of the United States, 1880-1907	128
IX.	Production of copper in the United States, 1882-1907	130
X.	Production of lead in the United States, 1880-1907	144
XI.	Production of zinc in the United States, 1880-1907	150
XII.	Map of Alaska, showing known distribution of mineral resources	172
FIGURE 1.	Curve showing production of coal, 1846-1907	26
2.	Curve showing production of iron ore, pig iron, and steel, 1870-1900	110

PAPERS ON THE CONSERVATION OF MINERAL RESOURCES.

INTRODUCTION.

This volume is a reprint of selected papers on the conservation of mineral resources, written by members of the United States Geological Survey in response to executive order, for the report of the National Conservation Commission (S. Doc. No. 676, 60th Cong., 2d sess.). Nearly all the information from which these papers are compiled had previously been collected by the Geological Survey in the performance of its regular duties. Since the organization of the Survey the mineral resources of the nation have been the principal subject of its investigations, and the data on which are based the estimates of the reserves of mineral fuels and ores are the results of nearly thirty years of official work. The report on the coal fields is practically a restatement of the information set forth on the coalfield map published in May, 1908, before the appointment of the National Conservation Commission; the other inventories constitute a summation of work in which the authors had been engaged as members of the Survey. The printing of the conservation report has furnished an opportunity to present these reprints in convenient form and, as the demand for the larger report will greatly exceed the edition authorized, this segregation of the papers relating to minerals will prove useful.

[Map of Distribution of Coal Fields in the United States Omitted]

COAL FIELDS OF THE UNITED STATES

By MARIUS R. CAMPBELL and EDWARD W. PARKER.

INTRODUCTION

According to the estimates prepared by the U. S. Geological Survey, the area underlain by workable coal beds in the United States is 496,776 square miles. Of this total area, 480 square miles contain the entire anthracite coal fields of Pennsylvania. The bituminous coal fields are estimated to be contained in an area of 250,051 square miles. The grade of coal between bituminous and lignite, which is designated by the Geological Survey as "subbituminous," is estimated to be contained within areas aggregating 97,636 square miles, while the areas containing lignite aggregate 148,609 square miles. The coal fields are divided, for the sake of convenience in classification, into six provinces, as follows (see Pl: I):

1. The eastern province, containing the anthracite coal fields of Pennsylvania and the bituminous coal fields of the Appalachian region, i.e., those of western Pennsylvania, Ohio, Virginia, West Virginia, Kentucky, Tennessee, Georgia, Alabama, and small outlying areas of North Carolina.

2. The interior provinces, containing the bituminous coal-producing regions of Michigan, Illinois, Indiana, western Kentucky, Iowa, Kansas, Missouri, Oklahoma, Arkansas, and Texas.

3. The Gulf province, containing the lignite areas of Alabama, Mississippi, Louisiana, Arkansas, and Texas.

4. The northern Great Plains province, containing the lignite subbituminous areas of North and South Dakota, eastern Montana, and northeastern Wyoming.

5. The Rocky Mountain province, containing the bituminous and subbituminous areas of western Montana and western Wyoming, Colorado, Utah, and New Mexico.

6. The Pacific coast province, containing the areas of Washington, Oregon, and California.

During the last few years the Survey geologists have worked in all of these coal areas and have also been making careful estimates of the quantity of coal contained in the beds when mining first began. In making these estimates care has been taken to ascertain how much of the supply is easily available and how much is either not available under present mining and market conditions or is available with extreme difficulty. According to these estimates the quantity of coal contained within the known area of the United States when mining first began was 3,076,204,000,000 tons. Of this quantity a little less than two-thirds, or 1,922,979,000,000 tons, is considered as coal that is easily accessible of minable under present conditions, while slightly more than one-third, or 1,153,-225,000,000 tons, is considered as non-minable under present conditions or accessible with extreme difficulty. It should be remembered, however, that the quantity of coal given above as easily accessible includes the lignites and subbituminous coals of the Western States, of which approximately 530,000,000,000 tons, while easily accessible, can not be considered available under present conditions or those which may be expected in the near future. This would reduce the original supply of easily accesssible and available coal to approximately 1,400,000,000,000 tons.

The area of the different provinces and the quantity of coal contained therein when mining first began are shown in the following table:

Tonnage (short tons), by provinces and accessibility.

[Tabular Matter Omitted]

The distribution of this original supply of coal, according to grades and accessibility, is shown in the following table:

Tonnage (short tons), by grades of coal and accessibility.

[Tabular Matter Omitted]

The first mining of coal in a commercial way, in the United States, was in what is known as the Richmond basin, a small area in the eastern part of Virginia. Small quantities of coal had been mined here in the latter part of the eighteenth century and it was also in the latter part of the eighteenth and the beginning of the nineteenth centuries that efforts were being made to introduce anthracite coal for fuel purposes. The first actual records of the production of Virginia coal were in 1822, in which year it was reported that 54,000 tons were mined. In 1820 (two years before) 365 long tons of anthracite coal, or 1 ton for each day of the year, had been shipped to distant markets. From these small beginnings of less than a century ago the production of coal has increased until in 1907 the total output of anthracite and bituminous coal approximated 500,000,000 tons. In 1837 the total production of the United States reached, for the first time, a total exceeding 1,000,000 tons, the output being reported from 4 States only—Pennsylvania, Virginia, Kentucky, and Illinois—although Maryland also was producing a small quantity of coal at that time. In 1840 the production amounted to a little over 2,000,000 tons, the output being reported from 13 States. Ten years later, in 1850, the production amounted to 7,000,000 tons; in 1860 it was over 14,000,000 tons; in 1870 over 33,000,-000 tons; in 1890 it approximated 160,000,000 tons; in 1900 it was nearly 270,000,000 tons; and in 1907 it was 480,000,000 tons. The aggregate production to the close of 1907 has amounted to 6,865,097,567 short tons.

Up to the close of 1845 the total production of coal in the United States was 27,700,000 short tons, and since that time the drain on the supply has practically doubled with each decade. The total production to 1845 and decenntially since that time has been as follows:

	Short tons
Up to 1845	27,677,214
1846-1855	93,417,827
1856-1865	173,795,014
1866-1975	418,425,104
1876-1885	847,760,319
1986-1995	1,586,008,641
1896-1905	2,832,402,740
1900-1907	894,520,702
Total	6,805,097,567

It is estimated that for every ton of coal mined and sold, half a ton is lost or wasted, so that the total production of 6,865,097,567 short tons to the close of 1907 represents an exhaustion of 10,200,000,000 tons, or 0.3 per cent of the total original supply, or 0.7 per cent of the coal which is easily accessible and available under the present conditions. The total supply of easily accessible and now available coal left in the ground at the close of 1907 was 1,382,780,000,000 short tons.

Accompanying this statement two charts are presented, one showing the production of coal annually from 1840 to 1907, the other illustrating the average annual production by progressive ten-year periods for the same length of time, the latter chart having been prepared in order to eliminate minor variations due to abnormal conditions. The average annual increase in coal production figured from the average of progressive decades shown on the second diagram is 7.36 per cent, and for the last five progressive decades—1894-1903 to 1898-1907—the rate of increase has been above that average.

DURATION OF SUPPLY.

The total reserve of easily accessible and now available coal is estimated at 1,382,780,000,000 tons. The assumption that a constant output has been reached would be utterly unwarranted. On the other hand, the adoption of the flat rate of annual increase of 7.36 per cent would involve the improbable assumption that the marvelous record of the past and present will be maintained in the future and the production would continue to approximately double every decade. Using the waste allowance, on the basis of this constant rate of increase in producton, the 1,382,780,000,000 tons available at the close of 1907 would be exhausted in one hundred and seven years, or by 2015 A. D. Against the use of the flat rate of increase it may well be contended that just as the rate of increase in population tends to diminish, so this rapid increase in per capita consumption of coal cannot persist, and a constant annual production will be reached. However, the figures set fifty years ago by statisticians for the probable constant annual production of coal in England have already been exceeded by over 160 per cent.

Mr. Henry Gannett has made an estimate based upon a decreasing rate of increase calculated from twenty-year averages of production. The use of ten-year averages is regarded as unsatisfactory for the reason that one of the decades may consist mainly of a period of prosperity, while the preceding and succeeding decades contain periods of business depression. The twenty-year period, however, is sufficently long to include a period of prosperity with one of business depression. Taking the four twenty-year periods since 1828, three rates of increase are obtained which show a rapid decrease. The hyperbolic curve computed from these successive rates of increase will indicate the constantly diminishing rate of increase for the successive twenty-year periods. The result obtained by this method is that the easily accessible and available coal will be exhausted about the year 2027, and all coal by the middle of that century. It is recog-

nized that the data upon which this curve has been constructed are few and the curve correspondingly weak. However, in the above estimate all of the data have been given which it is possible to use, and this estimate is believed to represent the best use that can be made of the data at hand.

Inasmuch as America leads the world not only in present production of coal, but also apparently possesses the greatest reserve and certainly is mining coal at much lower cost than any other country, the obvious tendency will be for European countries to look more and more to the United States for their coal supply. Therefore, while our present coal production and consumption are practically equivalent, the export of coal, unless prohibited by federal legislation, must eventually become a factor and increase the coal production in the United States beyond the demands of home consumption. On the other hand, powerful influences will come to bear upon coal production, which favor lengthening the life of the supply. Thus it is to be hoped that with more improved methods in the utilization of coal the increased efficiency per unit may act as a factor in reducing coal consumption, and improved mining methods should likewise decrease the waste percentage. The increased utilization of water power should also tend to decrease coal consumption. Again, as soon as the end appears in sight prices will rise and production diminish, and that progressively. This interference with the law of decreasing increase produced by growing scarcity will of course, prolong the life of our coal reserves, but at the same time will greatly hamper our industries that depend on this fuel.

With so many indeterminate factors whose importance is realized but can not be measured, prophecy must possess a questionable value.

WASTE IN COAL MINING.

The principal loss or waste attending coal-mining operations is that represented by the quantity of coal necessarily

left in the ground as pillars to support the roof. In some cases it is also necessary to leave a foot or more of coal as a part of the roof, because of the unstable character of the material overlying the coal, which itself does not make a good roof. It has also been frequently the case that, where portions of the coal bed have been of inferior quality, only the high-grade coal has been mined and the poorer material left. The coal left as pillars, or as portions of the roof, may be considered a necessary loss, but that which is left because of its inferior quality can not be considered unavoidable waste in any sense, and is frequently of higher grade than coals mined and used in other portions of the country.

Enormous quantities of coal have been lost beyond recovery from the mining of beds lying below, the caving of which, upon the withdrawal of the pillars, has so broken up the overlying strata as to render it impossible to recover the coals contained therein. This has been particularly the case in some of the coal beds of western Pennsylvania, but much improvement has been observed in this regard within later years. Notwithstanding the improvement in this respect it is probable that a large amount of coal will be wasted in the Western States, where a great number of coal beds are closely associated, and also where the intercalated strata are weak, forming poor roofs to the mines.

There are no exact figures as to the actual loss or waste sustained through coal left in the mines in conducting the mining operations, but it has been estimated that it amounts to 50 per cent of the quantity produced and marketed. In some cases, through careful mining and where the conditions are ideal for working, practically all of the contents of the coal beds are recovered. In other cases, particularly when the beds are of enormous thickness, the recovery has not exceeded 30 per cent of the contents. During the earlier days of mining in the anthracite regions of Pennsylvania it was estimated that only

40 per cent of the coal was marketed. This was partly due to uneconomical methods of mining, and partly to the large amount of culm, for which there was at that time no market and which was piled on the ground in unsightly mountains. At the time of the Anthracite Coal Waste Commission, which made its report in 1893, 40 per cent was still considered a maximum recovery. So far as underground workings are concerned, there has been no revolution in the methods employed since that time, but there has been a considerable improvement in the application of those methods, which has resulted in the recovery at the present time of a materially larger proportion of the coal in the ground than was the rule at that date. The earlier methods of mining consisted in leaving comparatively narrow pillars, and in the mining of large rooms the result was that the pillars were not strong enough to stand the pressure and were crushed beyond recovery. It is now customary to use larger pillars between the rooms, which makes it possible to better control the roof during "robbing" operations and to eventually recover a larger proportion of the contents of the bed.

Material improvements have also been made in the methods of the preparation of coal, so that a much greater proportion of the product hoisted is now being sent to market in merchantable condition. Part of this is due to better and more systematic methods of handling, and part to the saving of small sizes which formerly went to the culm banks. The higher prices of coal and the development of methods for using these small sizes have also made it possible, through washing processes, to rework the small coal formerly thrown on the clum banks, and these are now furnishing several millions of tons of marketable coal annually.

Under present conditions, except in cases where the surface must be maintained, it is estimated that in the Wyoming region of the Pennsylvania anthracite field the recovery for market is from 60 to 64 per cent. In the

Lehigh, Mahanoy, and Schuylkill regions the recovery for shipment is estimated at 56 per cent.

When the Anthracite Coal Waste Commission [a] made its report in 1893 the shipments of anthracite had amounted to 820,362,995 long tons, and the total production was estimated to have been 902,000,000 long tons. The commission estimated that for every ton produced, 1½ tons were lost, and the total exhaustion was estimated at 2,255,000,000 long tons. The estimated original contents of the field were 19,500,000,000 tons, and the estimated contents remaining at the beginning of 1893 were 17,245,000,000 tons.

The commission in its report (p. 149) says:

> It is to be doubted whether the total coal won when the field shall be abandoned will exceed 40 percent of the total contents. An estimate on that basis would show the available marketable coal still now in the ground to be as follows:

	Tons
Wyoming region	1,859,000,000
Lehigh region	477,500,000
Schuylkill region	4,581,500,000
In all	8,898,000,000

> The amount of coal won at the modern colliery due to improvements in mining methods, in the appliances for handling the coal, and in the utilization of the small sizes shows a decided advance over the earlier years of mining; a still further advance will undoubtedly be made in these directions, and the mining of the small beds, where a larger per cent can be won, will all tend to increase the total. Future estimates for a long time will in all probability show an advance in the total per cent won.

What the commission predicted in the foregoing paragraph has to some extent already been accomplished, from

[a] The members of the commission were Eckley H. Coxe, of Drifton; Heber S. Thompson, of Pottsville; and William Griffith, of Scranton, Pa.

the fact that coal is now being mined from beds that were not considered a part of the available reserves when the commission made its report. In mining methods, as previously stated, there has also been a marked improvement, and the writers are of the opinion that it is safe to assume that since 1893 the 1 ton of coal lost for every ton mined is nearer the actual results than 1½ tons lost for each ton mined, and at this rate the available supply at the beginning of 1893 would have been 8,622,500,000 tons instead of 6,898,000,000 tons. The total production from 1893 to the close of 1907 has amounted to 833,187,445 long tons, which deducted from the estimated available supply of 8,622,500,000 tons would leave as the remaining available supply 7,789,312,555 long tons, it being understood that this is only one-half of the coal left in the ground untouched. What may be done in the future in the way of recovery of coal which is now considered an absolutely necessary waste and lost for all time is, of course, a matter of conjecture.

In the mining of bituminous coal it is estimated that for every ton of coal produced for market one-half of a ton is lost or wasted. The part of this which is represented by the coal left in the mines for pillars, etc., may be materially reduced, but in many cases the recovery of a larger percentage of the coal in the ground can be obtained only by an increased cost of mining; and this in the face of the over-developed properties, keen competition, and low selling prices is incapable of accomplishment at the present day unless there be concerted legislative action by the governments of the several States.

There is another and a serious loss or waste in bituminous coal mining which is, like the culm in the anthracite fields, represented by the slack or fine coal necessarily or unnecessarily produced in mining operations. This is particularly the case when the coal is of the "dry" or noncaking variety which can not be used for coke making or which, because it does not fuse in the fire box, fails to make a satisfactory steam fuel. Many

thousands of tons of this "slack" coal are thrown on the ground each year, and much of it is burned in order to prevent it from "cumbering the ground" or adding extra weight above the mine workings. A large part of this waste could be presented by briquetting, but the process of briquetting adds about $1 per ton to the cost of the fuel, which renders competition with the cheap fuel in the shape of raw coal impossible. Two of the causes which lead to the production of unnecessarily large quantities of slack are the excessive use of powder and the practice of "shooting from the solid." These reduce the percentage of large-sized or marketable coal and naturally increase the cost of that portion of the product.

Legislation prohibiting shooting from the solid, which would provide penalties for excessive use of powder, would have as one result a larger percentage of lump coal; and thus in a measure enable operators to assume the additional expense involved in the briquetting of such slack coal as is unavoidably produced.

This legislation is the province of the state governments, and it is not too much to hope that before long laws may be enacted against the accumulation of slack heaps or their useless destruction by burning, and this waste prohibited, as that of natural gas has been in some cases.

The question of the waste in the combustion or utilization of coal does not come within the scope of this paper, but as the manufacture of coke is, in reality, a preparation of the fuel for use, attention may properly be called to the enormous waste resulting from beehive oven practice (the method commonly employed in the United States).

In what is known as the beehive oven (so called because of its similarity in shape to the conventional beehive) the coal is partially consumed, or, more properly speaking, the volatile combustible contents are consumed and all of the valuable constituents of the coal, except the fixed carbon, which is left behind as coke, are wasted. These

wasted constituents consist of gas, tar, and ammonia. In what are known as by-product recovery ovens, however, the process is one of distillation and the by-products of tar and ammonia and all of the gas, except that used for heating the ovens, are recovered and used.

The United States is far behind Germany and other foreign countries in adopting the economies resulting from the coking of coal in by-product ovens. In Germany at the present time little or no coke is made except in retort ovens. The first ovens of this type in the United States were built in 1898 at Syracuse, N. Y. Up to the close of 1907 the total number of this type of ovens completed was 3,892, while the number of beehive ovens in operation in that year was 94,746. The production from the retort ovens was 5,607,899 short tons of coke and that from beehive ovens 35,171,665 tons.

When the economies which may be effected by the use of the retort ovens have been so clearly demonstrated, not only by the plants which have been constructed in the United States, but more emphatically through the much more extensive development of by-product coke manufacture in Europe, the condition in the United States, as shown by the statistics for the last four years, is somewhat difficult to understand. As previously stated, the production of coke in the by-product ovens of the United States in 1907 amounted to 5,607,899 short tons. It was valued at $21,665,157. The total value of by-products obtained in the manufacture of this coke was $7,548,071, this value and the quantity being distributed as follows:

Value of by-products obtained in manufacture of coke in retore opens in 1907.

[Tabular Matter Omitted]

The gas included in the foregoing statement is the "surplus" not consumed in the coking process and is either sold or used at manufacturing establishments operated in

connection with the coke-oven plant. In a few instances where the surplus gas is consumed by the producing companies the quantity is not measured, nor was any value placed upon it in the reports made to the United States Geological Survey. In such cases careful estimates have been made, based upon the average surplus gas obtained from similar coals used at ovens of the same type. The value, similarly estimated, has been placed at from 10 to 15 cents per thousand cubic feet.

The coal consumed in retort ovens in 1907 amounted to 7,460,587 short tons. The quantity of coal used in beehive ovens was 54,485,522 short tons, from all of which the possible by-products are apparently wasted. Assuming that the coal consumed in beehive ovens was of the same average quality as that charged into the retort ovens and that the prices would be not less than 80 per cent of those ruling in 1907, the value of recoverable products which were thus apparently wasted last year amounted to $44,000,000, a sum equal to nearly 80 per cent of the total value of all the coal used in beehive ovens during the year. At the prices which prevailed in 1907 the value of the by-products wasted in beehive coke ovens was a little over $55,000,000.

The value of the by-products from the retort ovens in 1907 was a little more than one-third the value of the coke produced in them.

It should be remembered, however, that beehive ovens are located in the coal-mining regions and that the cost of the coal charged into them represents only a little more than that represented by the expense of mining the coal, whereas in locating by-product recovery plants provision must be made for utilizing or marketing the by-products. It is for this reason that in much the larger number of cases the recovery plants are established near the larger cities and at considerable distances from the mining regions, and the expense of transportation is added

to the mining cost of the coal. Hence it is that the value of the coal charged into by-product ovens in 1907 was $15,874,430, or over $2 per ton, while that of the coal used in beehive ovens was $56,956,008, or $1.05 per ton. It must also be remembered that the original cost of installation for a by-product plant is from four to five times that of a beehive plant of equal capacity. These disadvantages are in turn partly offset by the higher percentage of yield of coke in the retort ovens and a lower delivery charge on the coke produced. In the case of beehive coke, railroad transportation expense is borne by the coke, while in retort-oven practice all, or nearly all, of the freight charge is borne by the coal.

The total value of the 5,607,899 tons of by-product coke produced in 1907 was 21,665,157, an average of $3.86 per ton. The value of the 35,171,665 tons of beehive coke made in 1907 was $89,873,969, or $2.56 per ton. If we consider that the difference in the value of the by-product coke and beehive coke was due only to the difference in freight charges, then the total value of the entire product of beehive coke made in 1907 would, if made in retort ovens close to the market, have been $135,750,000. On adding to this the value of the by-products that should have been recovered, amounting to $44,000,000 at 80 percent of the market price in 1907, the total value of the coke and by-products would have amounted to nearly $180,000,000 instead of the value of $89,873,969 for the beehive coke alone. The value of the coal charged into these ovens, however, would have been $108,879,870 instead of $56,956,008. Carrying the hypothesis further, the difference between the value of the coke and by-products if the coal had been coked in retort ovens and the value of the coke alone from the beehive ovens was, say, $90,000,000. From this should be deducted the difference between what the value of the coal would have been at retort ovens and what it was at beehive ovens, i.e., $52,000,000. The remainder ($38,000,-

000), less the difference in operating expenses, wear and tear, interest on capital, etc., may be considered as approximately the actual net loss in value as the result of beehive coke production compared with by-product coke practice in 1907.

One of the reasons that has been given for the apparent lack of progress in retort-oven building in the last four years is the lack of profitable markets for the by-products of coal tar, and this has contributed to the backwardness of the United States in the development of the chemical industries depending upon coal tar as a raw material, and yet this country is importing coal-tar products to the value of several million dollars annually. It is also well known that the development of the coal-briquetting industry has been retarded because of the lack of assurance of a satisfactory supply of suitable coal-tar pitch for binding material, and there is also an increasing demand for creosoting oils for the preservation of timber.

COAL SUPPLY, PRODUCTION AND EXHAUSTION, BY STATES.

Alabama.—As far as known the earliest record of the existence of coal in Alabama was made in 1834. The first statement of production is contained in the United States Census Report for 1840, in which year the production is given at 946 tons. In 1907 the production was 14,250,454 tons, and the total production from 1840 to 1907 amounted to 164,734,310 short tons, which represented an exhaustion, including the waste in mining, of 247,000,000 tons. The total coal-bearing area of the State is estimated at 14,430 square miles, and the original coal supply is estimated to have been 68,903,000,000 short tons. The exhaustion to the close of 1907 represents a little over 0.3 of 1 per cent, and the production in 1907 was a little over 0.02 of 1 per cent of the estimated original supply.

Arizona.—A small area of 30 square miles in Arizona is estimated to contain 60,000,000 tons of coal, from which there had been no production at the close of 1907.

Arkansas.—As in Alabama, the first production of coal reported in Arkansas was in the census year 1840, when 220 short tons were reported as having been mined in that State. The industry in Arkansas did not develop rapidly during the early years, as the census of 1860 shows a production of only 200 tons, and that of 1880 a total of 14,778 tons. During the last twenty years, however, there has been a marked increase in the production of coal in Arkansas, and the maximum output was reached in 1907, with a total of 2,670,438 short tons. The total production to the close of 1907 amounted to 23,756,401 short tons, equivalent to an exhaustion of approximately 36,000,000 tons. The estimated original supply of coal in Arkansas was 1,887,000,000 short tons, of which the exhaustion to date represents practically 2 per cent The production in 1907 was equivalent to 0.15 of 1 per cent of the estimated original supply. The total area in Arkansas which contains workable coal or which may contain workable coal or lignite is estimated to be 7,584 square miles.

California.—The coal fields of California consist of scattered areas, of which, with few exceptions, comparatively little is known. The total workable area is estimated to be 500 square miles, and the original contents of the field 1,000,000,000 short tons. Mining in California had its beginning, according to the records of the state mining bureau, in 1861. The maximum production was reached in 1880, since which time the production has been irregular and has shown a declining tendency, this being due in the last few years to the increased production of oil in the State and its use for fuel purposes. The total coal production to the close of 1907 was 5,030,945 short tons, eqivalent to an exhaustion of approximately 7,000,000 tons, or 0.7 per cent of the original supply.

Colorado.—Colorado is one of the Western States which is rich in coal resources. The estimated total area of the coal fields is 17,180 square miles, and the original contents of these fields are estimated to have been 371,770,000,000 short tons. Coal production began in Colorado in 1864, but it was not until 1882 that the output reached as much as 1,000,000 short tons. Since that date there has been a steady increase in production, until in 1907 it amounted to 10,790,236 short tons. The aggregate production to the close of 1907 was 112,668,336 short tons, of which the equivalent exhaustion has been 169,000,000 short tons, which represents a little over 0.05 of 1 per cent of the original supply. The production in 1907 was approximately 0.004 of 1 per cent of the original contents of the fields.

Georgia.—The coal fields of Georgia are limited to a small area in the northwestern part of the State, estimated to cover 167 square miles and to have contained, when mining began, 933,000,000 short tons. The census report for 1860 contains the first authentic statement of production in Georgia, and the output in that year is placed at 1,900 short tons. The production of the State in 1907 was 362,401 tons, and the total production to the close of the year was 8,123,696 short tons, representing an exhaustion of 12,000,000 tons. This would still leave in the ground a total of 921,000,000 tons, of which 650,000,000 tons would probably be considered as the available supply, and this, at the rate of production in 1907, would last approximately 1,800 years.

Idaho.—The areas in Idaho known to contain workable coal are placed at 200 square miles, while there are 1,200 square miles which are not known, but which may also contain workable coal. The estimated original contents of the coal field of Idaho are placed at 600,000,000 tons, from which to the close of 1907 less than 25,000 tons had been mixed.

Illinois.—Illinois is the second State in coal-producing importance. The area in Illinois known to contain coal is larger than that of any other State east of the Mississippi River, and if we consider only the known coal areas the coal fields of Illinois cover a wider area than those of any other coal-producing State. The coal-producing area of Illinois is estimated at 35,600 square miles, and the original contents of the fields are placed at 240,000,000,000 short tons. The earliest mention of coal in the United States is contained in the journal of Father Hennepin, a French missionary, who, as early as 1679, reported a "cole mine" on the Illinois River, near the present city of Ottawa. The earliest record of actual mining is that coal was produced in Jackson County in 1810. In 1833 the production is reported to have been 6,000 short tons. In 1907 it was 51,317,146 short tons. The total production to the close of 1907 amounted to 645,868,309 tons, representing an exhaustion of 968,000,000 short tons, from which it appears that the exhaustion to the close of 1907 has been 0.4 of 1 per cent of the total estimated supply. The quantity of coal remaining in the ground at the close of 1907 was 4,664 times the production of that year, or about 2,500 times the exhaustion represented by that production.

Indiana.—The coal fields of Indian lie entirely in the southwestern portion of the State. They are confined within an estimated area of 6,500 square miles, and contained, when mining first begun, 44,169,000,000 tons of coal. Coal mining in Indiana began sometime between 1830 and 1840, and the census of the latter year reported a production of 9,682 tons. In 1907 the production amounted to 13,985,713 short tons, and the total production to the close of that year amounted to 159,440,390 short tons. The exhaustion to the close of 1907 had been 239,000,000 short tons, or 0.54 of 1 per cent of the original supply. Upon these estimates the quantity of coal remaining in the ground in Indiana at the close of 1907 was about 3,000 times the production of that year, and 2,000 times the exhaustion represented by that production.

Iowa.—The coal fields of Iowa are estimated to contain workable coal aggregating 12,560 square miles. To this may be added 5,640 square miles of possible workable coal areas. The original contents of the fields are estimated to have been 29,160,000,000 short tons. From this there has been produced from 1840, when mining first began, to the close of 1907, a total of 141,608,792 short tons, representing an exhaustion of 212,000,000 short tons. The quantity of coal still available at the close of 1907 was 28,948,000,000 short tons. At the rate of production in 1907, in estimating half a ton lost for every ton mined, this supply would last 2,550 years.

Kansas.—The areas in Kansas known to contain workable coal are placed at 3,100 square miles, although in addition to this there are 15,780 square miles which may contain workable coal. The estimated supply, when mining first began, is placed at 7,022,000,000 short tons. From this there has been produced from 1869 (the year of earliest production) to the close of 1907 a total of 91,176,204 short tons. This represents an exhaustion, including loss in mining, of about 136,000,000 short tons, from which it would appear that about 1.9 per cent of the original supply has been exhausted. The production in 1907 was 7,322,440 short tons, equivalent to an exhaustion of 10,000,000 short tons, which would indicate, at the rate of production in 1907, that the known coal supply of Kansas would last approximately 700 years.

Kentucky.—Kentucky is the only one of the coal-producing States which has within its borders areas belonging to two of the great coal fields. The eastern counties of the State are underlain by the coal beds of the great Appalachian system, while the southern limits of the central or eastern interior field are found in the more northern counties of the western part of the State. The eastern areas contain 10,270 square miles, the contents of which, when mining began, are 6,400 square miles, the contents of which, when mining began, are estimated at 67,787,000,000

short tons. The western areas contain 6,400 square miles, the original contents of which are placed at 36,240,000,000 short tons. The total estimated original supply of the State was therefore 104,027,000,000 short tons. Mining began early in the second quarter of the nineteenth century, and it is estimated that from 1829 to 1835 the production ranged from 2,000 to 6,000 tons a year. The production in 1907 was 10,753,124 short tons, and the total production to the close of the year was 122,404,574 short tons, which represents an exhaustion of 184,000,000 short tons, or 0.18 of 1 per cent of the original supply. The quantity of coal left in the ground at the close of 1907 would then be 103,844,000,000 tons, of which approximately 67,000,000,000 short tons would be considered available, or, in other words, the supply at the close of 1907 was 6,700 times the production in that year.

Maryland.—The coal fields of Maryland are confined to a limited area in Allegany and Garrett counties in the western part of the State. This area has an extent of 455 square miles and the original supply is estimated to have been 8,044,000,000 short tons. Mining began early in the nineteenth century, and shipments were made down the Potomac River in 1830. The first shipments by railroad were made in 1842, in which year 1,708 tons were shipped over the newly built Baltimore and Ohio Railroad. In 1907 the production amounted to 5,532,628 short tons, and the total production to the close of that year aggregated 147,606,548 short tons, equivalent to an exhaustion, including waste, of 221,000,000 tons, or not quite 3 per cent of the original supply. The supply still remaining at the close of 1907 was 7,823,000,000 short tons, 1,422 times the production and 948 times the exhaustion represented by the production of that year.

Michigan.—The coal fields of Michigan are the only ones within the drainage basin of the Great Lakes. They occupy an area of approximately 11,000 square miles and are estimated to have contained when mining first

began a total of 12,000,000,000 short tons of coal. Although coal mining has been carried on in Michigan for about seventy years, it is only a little more than a decade since it became of any importance as an industry, the production exceeding a million tons a year for the first time in 1901. The total production to the close of 1907 was 13,842,943 short tons, which, including waste, represents an exhaustion of 21,000,000 short tons, or 0.175 of 1 per cent of the total original supply. The production of Michigan in 1907 was 2,035,858 short tons. The supply remaining at the close of that year was, according to the best estimates, 11,979,400,000 short tons, of which 7,986,000,000 tons would be considered as available. This is equivalent to 3,900 times the production of 1907.

Missouri.—The original coal supply of Missouri is estimated to have been 40,000,000,000 short tons, included within an area of 23,000 square miles. The production of the State to the close of 1907 had amounted to 97,618,106 short tons, representing an exhaustion of approximately 146,000,000 tons, or 0.36 of 1 per cent of the original supply. The production in 1907 was 3,997,936 short tons, which is equivalent to an exhaustion of approximately 6,000,000 tons. The supply remaining at the close of 1907 is about 6,500 times the exhaustion created by the production in that year.

Montana.—Montana's scattered coal fields, known to contain workable coals, aggregate 34,067 square miles, while the areas which may contain workable coal, but which are not well known, amount to 17,575 square miles. The original contents of these coals fields are estimated to have been 303,060,000,000 short tons, from which there have been mined to the close of 1907 approximately 24,740,000 tons, representing an exhaustion of 37,000,000 tons, or 0.012 of 1 per cent of the original supply. The production in 1907 of a little over 2,000,000 tons is equivalent to an exhaustion of about 3,000,000 tons, and the coal left in the ground was 100,000 times that exhausted.

New Mexico.—The coal fields of New Mexico aggregate a total area of 18,335 square miles, and the original supply is estimated to have been 163,780,000,000 short tons, from which there had been produced to the close of 1907 a total of 22,325,432 short tons, representing an exhaustion of 33,000,000 tons, or 0.02 of 1 per cent of the original supply. The production in 1907 (2,628,959 short tons) is equal to nearly 12 per cent of the entire production of the coal to the close of that year, while the coal left in the ground is nearly 65,000 times the production in 1907, and over 40,000 times the exhaustion represented by that production.

North Carolina.—Two small areas of Triassic age contain all the coal known to exist in North Carolina. The total area is about 60 square miles, and the original contents of the field are estimated at 200,000,000 short tons. These areas have never been worked to any large extent, and the total production to the close of 1907 was less than half a million tons.

North Dakota.—Although the coal fields of North Dakota are of wide extent, the coal itself is all of lignitic character and of little commercial value at the present time. The total areas supposed to contain workable lignite are placed at 35,500 square miles and the original contents have been estimated at 500,000,000,000 short tons. The production, particularly considering the large supply, has been very small, the total exhaustion to the close of 1907 having amounted to only 4,000,000 tons.

Ohio.—Compared with the supply of coal originally contained within the coal fields of Ohio, the rate of exhaustion has been greater than that of any other State in the Appalachian system, with the exception of Maryland. The estimated original supply contained within an area of 12,660 square miles was 86,028,000,000 short tons. The first record we have of the production in the State is in the year 1838, when 119,952 short tons of coal were mined. Ohio's output was at that time exceeded

only by the production of Pennsylvania anthracite and bituminous coal from the Richmond basin. From 1845 to 1875 Ohio ranked second among the coal-producing States. In 1876 it was surpassed by Illinois, and since 1896, when it was surpassed by West Virginia, it has ranked fourth among the coal-producing States. In 1907 Ohio contributed 32,142,419 short tons of coal to the total product of that year. The total output of Ohio mines from 1838 to the close of 1907, a period of seventy years, has amounted to 492,769,358 short tons, representing an exhaustion of 739,000,000 tons, or something less than 0.9 of 1 per cent of the estimated original supply. The production of 1907, which was a little less than 7 per cent of the production to the close of that year, was equivalent to an exhaustion of about 48,000,000 tons. Deducting from the original supply the exhaustion at the close of 1907, there would still be available on January 1, 1908, 85,980,000,000 tons, or nearly 2,000 times the production in 1907.

Oklahoma.—All of the coal in Oklahoma is contained in that portion of the State which was formerly known as the Creek, Cherokee, and Choctaw nations of Indian Territory. The total area underlain by workable coal is estimated to be about 10,000 square miles, and the original contents are estimated to have been 79,278,000,000 tons. Mining did not begin in Indian Territory until comparatively late, the first production reported having been in 1880, when 120,947 short tons were produced. The industry has progressed rapidly, however, and the production in 1907 amounted to 3,642,658 short tons. The total production to the close of 1907 was 39,845,015 short tons, representing an exhaustion of approximately 60,000,000 tons. The quantity of coal left in the ground in Oklahoma at the close of 1907 was 13,000 times the exhaustion represented by the production in that year.

Oregon.—As far as known the earliest record of coal production in Oregon was in 1880, when the output

amounted to 43,205 short tons. In 1907 Oregon's production was 70,981 short tons, and the aggregate production from 1890 to the close of 1907 was 1,790,392 tons, which represents an exhaustion of 2,700,000 tons. The total area in the State containing workable coals is estimated at 230 square miles and the original supply at 1,000,000,000 short tons.

Pennsylvania.—The supplies of anthracite coal in Pennsylvania are discussed elsewhere in this paper. (See p. 13.) The bituminous areas in the western portion of the State are estimated to have an extent of 14,200 square miles and to have contained, when mining first began, 121,574,000,000 short tons. The development of the Pennsylvania bituminous coal fields did not begin until about twenty years after anthracite mining was established as an industry, the first production having been reported in the census year 1840, when 464,826 short tons were mined. Up to 1897 the production of anthracite coal in Pennsylvania exceeded that of bituminous, but in 1898 the bituminous production took the lead and has contained to lead since that date. In 1907 the production of bituminous coal exceeded that of anthracite by nearly 80 per cent, and as indicative of the extent to which the bituminous coal-mining industry of Pennsylvania has grown it may be stated that the production in 1907 was nearly three times that of 1897, only ten years before. The total production of bituminous coal in Pennsylvania to the close of 1907 was 1,846,069,253 short tons, which was equivalent to an exhaustion of 2,760,000,000 tons, or 2.5 per cent of the original supply. The exhaustion represented by the production in 1907 was 225,000,000 tons. The supply remaining at the close of 1907 was 109,804,000,000 tons, or 492 times the exhaustion represented by the production of that year.

South Dakota.—The northwest corner of South Dakota contains the southern extension of the North Dakota lignite beds, and it is estimated that about 6,000 square

miles of this territory may contain workable lignites. The contents are estimated at 10,000,000,000 short tons, and these are practically untouched.

Tennessee.—The coal fields of Tennessee are contained in a narrow strip in the eastern counties of the State, where the Appalachian province crosses the State in a northeast-southwest direction. Mining began sometime between 1830 and 1840, and the census for the latter year reported a production of 558 tons. Coal mining did not, however, develop into an important industry in Tennessee until after the close of the civil war, and it was not until 1883 that the production reached as much as 1,000,000 tons annually. Since that time it has increased with notable regularity, until in 1907 the production amounted to 6,810,243 short tons. The total area of bituminous coal in the State is estimated at 4,400 square miles, and the total original supply at 25,665,000,000 tons. The total production to the close of 1907 amounted to 84,304,601 short tons, representing an exhaustion of approximately 126,000,000 tons, or about 0.5 of 1 per cent of the original supply. The exhaustion represented by the production in 1907 was approximately 10,200,000 tons, and the supply left in the ground at the close of the year was equal to 2,500 times this exhaustion.

Texas.—The known bituminous coal fields of Texas are estimated to contain 8,200 square miles, and the exploited lignite fields 2,000 square miles. In addition to this there are 5,300 square miles which may contain workable bituminous coal and 53,000 square miles which may contain workable lignite. The estimated contents of the bituminous coal fields when mining first began in Texas were 8,000,000,000 short tons, and of the lignite fields 23,000,000,000 short tons. The exploitation of both the lignite and the bituminous areas is of comparatively recent date, no production having been reported from Texas prior to 1884, and it was not until 1901 that the output reached as much as 1,000,000 tons. The production to

the close of 1907 was 14,444,948 short tons, representing an exhaustion of 22,000,000 tons, or 0.07 of 1 per cent of the original supply.

Utah.—Utah's coal fields are contained in scattered areas aggregating 15,130 square miles. The quality of the coals ranges from subbituminous to anthracite. The estimated original supply was 196,458,000,000 short tons, from which the exhaustion, including waste, at the close of 1907, was 28,000,000 short tons, indicating that there were still remaning in the ground 196,430,000,000 tons, or a little more than 100,000 times the production of 1907.

Virginia.—The Richmond basin in Virginia, where coal mining in the United States was first carried on, contains 150 square miles. Another small area in Montgomery County contains 200 square miles of coal-productive territory, but the principal regions are in the southwestern corner of the State, which is crossed by the Appalachian system. The portion of the Appalachian coal field in Virginia is estimated to be 1,550 square miles. The original supply has been placed at 22,500,000,000 short tons. From this there has been produced at the close of 1907 a total of 67,229,152 short tons, representing an exhaustion of 36,000,000 tons. The production in 1907 was 4,710,895 short tons, equivalent to an exhaustion of a little over 7,000,000 tons, so that the coal left in the ground in Virginia at the close of 1907 was 2,000 times the exhaustion represented by the production of that year.

Washington.—Washington's coal supply is contained within a number of areas that are scattered over the State and aggregate approximately 1,100 square miles. The estimated original supply was 20,000,000,000 short tons, and while mining began there as early as 1860, the total production to the close of 1907 was only 43,108,697

short tons, of which nearly 50 per cent was produced within the last seven years. The exhaustion represented by the production to the close of 1907 was 64,000,000 short tons, which is equivalent to about one-third of 1 per cent of the original supply. The quantity of coal still in the ground at the close of 1907 was estimated to be 19,936,000,000 short tons, equivalent to 5,400 times the production of 1907 and 3,600 times the exhaustion made by that output.

West Virginia.—The total area containing workable coal in Virginia is 17,000 square miles, and the original supply when mining first began was 231,039,000,000 tons. West Virginia was not admitted as a State until 1863, in which year the production amounted to 444,648 short tons. The quantity of coal mined prior to that time, in the portion of Virginia which afterwards became West Virginia, was not sufficient to materially affect the total output. For a number of years West Virginia has been third among the coal-producing States, and in 1907 the production amounted to a little over 48,000,000 tons. The aggregate production to the close of 1907 was 434,198,539 short tons, equivalent to an exhaustion of 650,000,000 tons. At the beginning of 1908 there still remained available in the coal fields of West Virginia 230,389,000,000 short tons, nearly 4,800 times the production in 1907, or 3,200 times the exhaustion represented by the 1907 output.

Wyoming.—The estimated original coal supply of Wyoming is larger than that credited to any other coal-producing State, with the exception of North Dakota. In the latter State, however, the entire supply is lignite, while in Wyoming the coals are of subbituminous or of bituminous character. The total area which may contain workable coals has been estimated 50,793 square miles, and the contents of this field, when mining first began, at

[Chart Omitted]

424,085,000,000 short tons. In comparison the aggregate production at the close of 1907, which was 77,818,765 short tons, appears insignificant. The total exhaustion of the beds to the close of 1907 amounted to 116,000,000 short tons, or 0.027 of 1 per cent of the total estimated supply.

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, Director

BULLETIN 424

THE VALUATION OF PUBLIC COAL LANDS

THE VALUE OF COAL LAND

by

GEORGE H. ASHLEY

DEPTH AND MINIMUM THICKNESS OF BEDS AS LIMITING FACTORS IN VALUATION

by

CASSIUS A. FISHER

WASHINGTON
GOVERNMENT PRINTING OFFICE
1910

STANDARDS ADOPTED FOR COAL LANDS OF THE PUBLIC DOMAIN

In the classification of the coal lands remaining on the public domain the Director of the United States Geological Survey, with the approval of the Secretary of the Interior, has fixed 3,000 feet as the limit of depth of practical coal mining and 14 inches as the minimum thickness of a bed of coal which may be regarded as of workable dimension. The limit of depth chosen exceeds by only 800 feet the deepest coal beds which are actually being worked in this country and falls about 900 feet short of the depth at which coals are being successfully exploited in Belgium. It was clearly recognized in fixing this depth limit that 4,000 feet should be the limit consistent with present practice and experience in coal mining abroad. As the coals of the public lands, however, are in general of a medium grade and are located in the West, where their exploitation has only well begun, the time when coals on these lands lying between 3,000 and 4,000 feet below the surface would be worked is still remote. It was recognized that, under the present law, which does not permit the separation of surface and underground rights, the reservation of lands underlain by coals at these depths for mineral use only would prohibit the development of the surface features of such lands, which are of greater immediate value. The question became simply, For what use is the land most valuable? There was no doubt in the minds of those who fixed the depth limit of practical coal mining on the public domain at 3,000 feet that if the problem were considered in its broader aspect—that is, with a view to the future, in an endeavor to make the wisest disposition of the country's coal—the depth limit might properly be placed even at 4,000 feet.

In attempting to establish the minimum workable thickness of a coal bed it was hardly necessary, although very instructive, to look abroad for examples of thin-bed mining, for in parts of the Interior coal province of this country very thin coals are now worked. A minimum thickness of 14 inches does not seem extreme in any sense, as coal beds of this thickness are actually being worked by small mines in more than one locality in the Interior province and beds 2 to 4 inches thicker are being worked in several places by shipping mines of moderate size. This position is strengthened by the facts that in England and on the Continent coals considerably less than 14 inches thick are now being worked independently, and that for the last forty years, or since 1871, when the report of the first royal commission on coal supplies was made, 12 inches has been regarded in England as the minimum thickness of a workable coal bed.

The United States probably has greater coal resources than any other country and, as compared with England, has consumed a relatively small proportion of those resources; but these facts do not justify the practice of disregarding coals as of no value which, by reason of their great depth or their occurrence in thin beds, are difficult to mine. Surely in the United States, which ranks first in the world's production, it would be possible to win coal under as great difficulties as in any other country.

Of course it is to be expected that the question of mining coals at great depth and in thin beds in a commercial way will be regarded by the practical coal-mining man of to-day as more or less speculative. This criticism may be justifiable in a measure if the subject is viewed only in the light afforded by present commercial practices; but if it is considered with the broader view which notes the marked changes in conditions that are already manifesting themselves—such as the progress in obtaining greater heat values from coals, the greater specialization of their uses, and the certain exhaustion of thicker, shallower, and more valuable beds—it is certainly reasonable to expect that deep and thin coals will some day be mined in this country in a commercial way, as they are at the present time in other countries, where the main difference in conditions is that coal exploitation has reached a more mature stage.

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Technical Paper 2

DEPARTMENT OF THE INTERIOR
BUREAU OF MINES

JOSEPH A. HOLMES, Director

THE ESCAPE OF GAS FROM COAL

by

HORACE C. PORTER

and

F. K. OVITZ

WASHINGTON
GOVERNMENT PRINTING OFFICE
1911

CONTENTS.

	Page
General statement	3
Significance of results	3
Condition of the gas in coal	4
Previous investigations	5
Summary and interpretation of results	6
Procedure in experiments	8
Loss of heating value	13
Conclusions	13
Publications on fuel testing	13

ILLUSTRATIONS.

Figure 1. Rate of escape of methane from coal	11

THE ESCAPE OF GAS FROM COAL.

By HORACE C. PORTER and F. K. OVITZ.

GENERAL STATEMENT.

It is a matter of common knowledge that inflammable gas made up chiefly of methane, which forms with air the so-called fire damp of the miner, escapes from the coal in many mines; yet little is known as to the condition of this gas in the coal, its quantity and rate of escape. In addition to the gas set free by the coal itself, there is in many mines a large amount of inflammable gas that comes from reservoirs in the rock strata above or below the coal bed and enters the mine through cracks in the roof or floor. Gas entering the mine in such manner from extraneous sources is not considered in the following report, which presents rather some results of a laboratory investigation of the rate of escape of gas from several coals while kept in bottles connected to gas-collecting reservoirs. This investigation was begun by the United States Geological Survey and is being continued by the Bureau of Mines at the mining experiment station at Pittsburg, Pa.

SIGNIFICANCE OF RESULTS.

The results of the investigation show that gas escapes from coal not only during the breaking down of the coal in the mines, but also continuously for a long time after the coal is mined. The volume from some coals is so great as to merit serious consideration in connection with the ventilating of the mines and the choice of methods of breaking down the coal. For example, during the first two weeks after mining, there was set free by one coal, exclusive of the gas that escaped during mining, a volume of methane equal to three-fourths of the volume

of the coal itself.[a] Probably each cubic foot of this coal (in the seam) set free in all during its mining and during the first two weeks thereafter a cubic foot of methane. It was shown by further test that during the first five months after mining there was set free from this coal a volume of methane equal to one and three-fourths times the volume of the coal.

Many investigators, Chamberlin,[a] among others, have shown that methane accumulates along lines of fracture, such as joint cracks, within places of increased porosity in the coal bed and escapes from these as they are cut in mining. In any locality of the mine where for any reason adequate ventilation is not maintained, the methane which has thus escaped may become a source of danger from explosion.

CONDITION OF THE GAS IN COAL.

In some cases the volume of gas liberated from broken coal is greater than the volume of the coal itself—that is, of the actual solid and the cellular space combined. Several theories have been proposed to account for this fact. If the inclosed gas is mechanically imprisoned in the microscopic pores of the coal, it must be under a pressure greater than that of the atmosphere; otherwise it would occupy after its escape a volume less than that of the coal. It is possible, furthermore, that there is a continual slow formation of methane by chemical decomposition of the coal, or it may be that the gas is held in a state of occlusion—that is, either dissolved molecularly or adsorbed upon the inner surfaces of the cellular spaces.

The gas which escapes from coal has been very often called "occluded gas," but, as Chamberlin has made plain,[b]

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[a] See footnote, p. 10, for explanation of volume relations.

[a] Chamberlin, R. T., Notes on explosive mine gases and dusts with special reference to the explosions in Monongah, Darr and Naomi, Coal Mines, U.S. Geol. Survey Bull. 383, 1909, p. 32.

[b] Op. cit., pp. 16-17.

the word "occluded" has been loosely used in this connection, and the radical difference between mechanical imprisonment and true occlusion or condensation has been generally overlooked. The word "occlusion" properly implies the condensation of a gas within a solid substance to a state approaching that of liquid or solid, either condensed upon the interior surfaces of the pores or dissolved molecularly in the solid. The Century Dictionary defines occlusion as the absorption of a gas by a metal, as of hydrogen by palladium, in which case the hydrogen is regarded as existing in a solid form as a quasi metal. Mendelooff [c] states, "The capacity of certain dense metals for the absorption of hydrogen * * * is termed occlusion and presents a similar phenomenon to solution; it is based on the capacity of metals of forming unstable, easily dissociating compounds with hydrogen similar to those which salts form with water."

The results presented in this paper do not determine the condition of the gas in coal. The fact that the gas escapes without the aid of heat or of reduced pressure is hardly in strict agreement with the accepted idea of occlusion. But, on the other hand, Chamberlin [d] found that during the crushing of coal to 30-mesh size under a high vacuum there was liberated only about one-quarter of the total volume of methane obtained from the same coal while bottled for six months in vacuo. This fact is with difficulty explained by the theory of mechanical imprisonment under pressure, for it seems likely that in such case the walls confining the gas would be broken by the large excess of pressure within, and that the bulk of the gas would escape immediately. The theory that methane continues to be formed by slow decomposition of the coal explains satisfactorily many of the phenomena observed,

[c] Mendeloff, D. I. Principles of Chemistry, English Translation of 6th Edition, vol. 1, p. 143.

[d] Op cit. pp. 34-36.

but does not easily account for the decrease in the rate of escape of the methane.

Whatever may be the condition of the gas and its manner of liberation, the results presented in this paper clearly establish the fact that methane continues to escape from coal in considerable quantities and for a long period under atmospheric conditions of temperature and pressure. If allowed to accumulate, this slowly escaping methane in mines may become a source of danger even greater than the methane liberated in breaking down the coal. Calculations based on these results show further that contrary to common opinion the loss of heat value due to loss of methane in exposed piles of coal is probably in all cases so small as to be almost inconsiderable.

PREVIOUS INVESTIGATIONS.

Parr and Wheeler [a] have noted the accumulation of combustible gas from Illinois coals in laboratory sample bottles kept sealed for a year. They attribute to this fact part of the loss of heat value which they found in these samples. Many investigations have been made of the so-called occluded gas in coal, notably by Bedson,[b] McConnel,[c] Trobridge,[d] Parr and Barker,[e] and Chamberlin.[f] With the exception of Chamberlin these investigators have confined their attention to the gases drawn from coal by a reduction of pressure during a comparatively brief space of time. Their findings as to the quantity and the composition of the gases vary widely. The discrepancies are probably due not only to differences in the character of the coals, but also to the fact that most of the investigators

[a] Illinois State Geol. Survey Bull. No. 8, 1997, p. 106.

[b] Chem. News, vol. 68, 1883. p. 187.

[c] Jour. Soc. Chem. Ind., vol. 13, 1994, p. 36.

[d] Jour. Soc. Chem. Ind., Vol. 26, 1906, p. 1129.

[e] University of Illinois Eng. Exp. Sta. Bus. 33, 1909, pp. 10-28.

[f] Op. cit. pp. 16-39.

have taken little account of the gas that escaped in the interval between mining and testing. Parr and Barker took account of this factor by collecting 200-gram samples in flasks sealed in the mine and extracting the gases under vacuum on reaching the laboratory. They obtained in this manner from one Illinois coal 40 to 80 c.c. of methane and about 10 c.c. of carbon dioxide per 100 grams of coal, and showed also the rapid absorption of oxygen by fresh coal. Their experiments, however, did not take account of the gas liberated in breaking down the coal, nor did they study the escape of gas into an open space through an extended period of time. Chamberlin,[a] on the other hand, went further and not only extracted the loosely held gas of coal by crushing small lumps in a vacuum, but collected also considerable additional quantities of gas by keeping the crushed coal in a vacuum for six months. By crushing in vacuo to 10-mesh size coal from Monongah, W. Va., he obtained a volume of methane amounting, in different experiments, to 0.1 to 0.4 times the volume of the coal, and by keeping the crushed coal six months in vacuo he obtained an additional volume of methane 0.8 to 1.4 times the volume of the coal. The gas liberated in mining and during the deposit of the coal in covered cans to the laboratory was disregarded. Other gases extracted in Chamberlin's experiments were carbon dioxide (less than one-tenth of the volume of methane), and very small quantities of carbon monoxide and unsaturated hydrocarbons.

SUMMARY AND INTERPRETATION OF RESULTS

The experiments described in this paper supplement Chamberlin's work, and bring out the additional facts that methane and small quantities of carbon dioxide escape from coal for an extended period under atmospheric pressure, the amount of the gas and its rate of escape being nearly the same as when the coal is kept in a vacuum.

[a] U.S. Geol. Survey Bull. 383, pp. 17-39.

Furthermore, the experiments show that oxygen is absorbed rapidly by fresh coal and in quantities which are far out of proportion to the carbon dioxide liberated, if the latter be assumed to arise from combustion of the coal. The tabular statements and graphs on succeeding pages show the rate at which methane is liberated from several different coals.

Unfortunately, the results do not permit even an approximate estimate of the rate at which the different coals absorb oxygen. It is found late in the course of the experiments that the concentration of the oxygen available for action on the coal had much influence on the rapidity of the action, and this concentration had varied decidedly in the different tests. Ordinary air was used in some of the tests and oxygen, 95 per cent pure, in others. In all the experiments there is clearly shown, however, a rapid and long-continued absorption of oxygen, with little or no accompanying formation of carbon dioxide. Later experiments, now in progress in the laboratory in the Bureau of Mines, show that coals vary widely in the rapidity with which they absorb oxygen under like conditions.

The rapid absorption of oxygen by fresh coal without the formation of carbon dioxide is well illustrated by the coal from Connellsville, Pa. (No. 41, Table 2, p. 10.) Ten kilograms (22 pounds) of this coal absorbed during the first day after mining nearly half the oxygen in the 10 liters of air in the bottle and gave off little more than one-tenth as much carbon dioxide as would have been formed if all of the oxygen absorbed had combined with carbon to produce carbon dioxide.

The air of a closed mine, or of a poorly ventilated section of any coal mine, is usually deficient in oxygen, as compared with normal air, and contains much less carbon dioxide than will account for this deficiency on the basis

of the reaction of carbon and oxygen to form carbon dioxide.

This phenomenon is probably a direct result of the chemical addition of oxygen to the coal, since it is not likely that oxygen could be consumed in any other way without forming carbon dioxide, unless there were a fire in the mine, in which case oxygen would combine with hydrogen as well as with carbon. The oxygen absorbed from air by coal probably does not form directly either carbon dioxide or water, but is merely added, as suggested by Boudouard [a] and others, to certain compounds in the coal that are unsaturated with respect to oxygen and thereby produces humic acid or related substances.

The results presented show large variations in the quantities of methane liberated by the coals tested. A Kentucky cannel yielded only a trace of methane in nine months, while the Harrisburg, Ill., coal gave off one-fourth of its volume in four days, and the Monongah, W. Va., coal one-third of its volume in the same time.

These results are by no means to be interpreted as showing that some coals which yield little or no gas after mining are therefore not accompanied by gas in the mines. Pocahontas coal, for example, yields little methane after mining, but the mines in the western part of what is known as the Pocahontas district contain at times large quantities of gas. The methane which accumulates in coal mines may come, as before mentioned, from two sources—(1) from reservoirs of gas under pressure in the rock strata, and (2) from the coal bed itself, either from cavities where the gas has accumulated, or from a state of condensation or compression in the microscopic pores of the coal. The investigation discussed in this paper has to do only with the latter source, and although it advances data which emphasize the importance of the coal seam itself as a source of gas, it in no sense overlooks or lessens the importance of the inflow of gas from outside reservoirs.

[a] Bull. Soc. Chem., sec. 4, vol. 8, p. 390.

It is known that variations in atmospheric pressure have an influence on the accumulation of methane in mines. Apparently incompatible with this fact are the results presented in this paper, which show that methane escapes from broken coal at a rate practically unaffected by large reduction in pressure. Atmospheric conditions, however, may easily affect the escape of gas from the bed of coal in situ, since a slight fall in barometric pressure may open communication with cavities or crevices in the coal bed where gas is imprisoned under pressure, although the same decrease of pressure may have little or no effect on the gas that is more intimately imprisoned in the pores of the solid coal.

Carbon dioxide was found in the gases evolved by all the coals that are tested. The amount varied decidedly for the different coals; a maximum, from the Sheridan, Wyo., coal (No. 43), was 0.36 volumes in seven months. (See Tables 1 and 2, p. 10.)

PROCEDURE IN EXPERIMENTS.

A sample of approximately 10 kilograms (22 pounds) of the coal was taken from a clean, fresh face of the coal seam in the manner prescribed by the Bureau of Mines for mine sampling.[a] This sample was crushed so as to pass a ½-inch screen, and placed in a 5-gallon crated glass bottle, which was then stoppered as quickly as possible—usually within 50 to 80 minutes after beginning the cut. A tight-fitting rubber stopper was wired in. Through the stopper passed a 20-cm. (8-inch) length of glass tubing of 2-mm. (1/12-inch) bore, its outer end sealed by a piece of heavy rubber tubing and a solid glass plug. The crushed coal consisted largely of small lumps between one-tenth and one-half inch size but contained 10 to 20

[a] Bureau of Mines Technical Paper 1, The sampling of coal in the mine, by J.A. Holmes. 1911. 18 pp.

per cent of material under one-tenth inch in size. The bottle was shipped forthwith to the laboratory at Pittsburg. As soon as it arrived there the rubber stopper and connections were painted with shellac to avoid all risk of leakage, and a gas sample was at once withdrawn for analysis. The bottles were then allowed to stand in the laboratory several months at a temperature varying from 12° to 32°C.

Four coals, No. 37 (Pocahontas, Va.) No. 39 (Harrisburg, Ill.), No. 43 (Sheridan, Wyo.), and No. 49 (Benton, Ill.), were subjected to further investigation, as follows:

The bottle of Pocahontas coal (No. 37) was connected through the glass tube in the stopper to a reservoir of oxygen, so that the oxygen flowed into the bottle as fast as it was absorbed by the coal. From time to time the gas that accumulated in the bottle was drawn out in order to relieve the pressure and permit the inflow of oxygen. The bottles containing coals No. 39 and No. 43 were connected to a supply of air instead of oxygen and the inlet tube extended to the center of the coal in each bottle. There also was attached to each of these two bottles a collecting reservoir for the escaping gas, the connecting tube for this purpose passing from the top of the bottle to the reservoir. The bottle of Benton, Ill., coal (No. 49) was connected with both an oxygen supply and a gas-collecting reservoir, but oxygen, not air, was admitted to the bottle and was admitted at the top, the gas being withdrawn from underneath the coal.

The air, or oxygen, admitted was measured, and the gas withdrawn was measured and analyzed. Air, or oxygen, was admitted in slight excess so that every gas sample withdrawn contained some oxygen. It is hardly fair to compare the results of the test on Pocahontas coal with the results of the other tests, since in this test the accumulated gas was not withdrawn as regularly nor as rapidly

as in the others and the pressure within the bottle may have retarded the escape of methane from the coal. The test, however, serves to show that this coal evolves a comparatively small quantity of methane. A number of other coals were tested in somewhat similar manner, occasional samples of gas being taken from the bottle but without drawing off the accumulated gas into collecting reservoirs or admitting a supply of oxygen. The tests made in this manner are named in Table 2.

The gas samples were analyzed by the Hempel methods with certain modifications, as described in Bureau of Mines Bulletin 1, pages 22 to 24. Methane was determined always by the slow combustion method of Winkler. No attempt was made to determine less than 0.2 per cent of carbon monoxide, and since the first samples from the bottles showed less than that quantity of carbon monoxide and also of hydrogen and unsaturated hydrocarbons, no determinations of these three constituents were made thereafter.

Descriptive list of coals tested.

[Table Omitted]

TABLE 1.—*Gases given off and oxygen absorbed by four coals.*

[Table 1 Omitted]

TABLE 2.—*Gases given off and oxygen absorbed by five coals.*

[Table 2 Omitted]

[Figure 1 Omitted]

The difference in the rate of escape of methane from the coals is shown graphically in figure 1.

The results given in the tables and shown in figure 1 emphasize the gradual decrease in the rate of escape of methane and, in some cases, the ending of the liberation of methane within five months. The escape of methane from the two southern Illinois coals appeared to continue for a longer time, but even these coals showed a well-marked tendency to stop giving off gas. The dotted portions of the curves in figure 1 indicate the probable liberation of methane after the last measurement. The experiments with the coals from Monongah, W. Va., Hanna, Wyo., and Connellsville, Pa., were not carried far enough to show the rate of continuous escape of methane, but show the large quantity of methane set free by these coals just after mining. The coals from Rock Springs and Sheridan, Wyo., Paintsville, Ky., and Pocahontas, Va., do not appear to contain much inclosed gas. The results from the Harrisburg, Ill., coal (No. 39) are particularly instructive in showing, under conditions permitting good circulation of air, the gradually diminishing escape of methane, the long-continued absorption of oxygen, and in particular a steadily increasing liberation of carbon dioxide. This last phenomenon has been noted by Chamberlin,[a] and seems to indicate that either carbon dioxide is more tenaciously held in coal or, because of its greater density, does not diffuse as readily as methane. It is of interest to note in this connection the results from the Rock Springs and Sheridan, Wyo., coals and the Kentucky cannel coal, all of which yielded at the start greater quantities of carbon dioxide than the coals that were more highly charged with methane.

In a few instances, during the analysis of the hydrocarbons in the gases, a small proportion of ethane was indicated by the presence after combustion of slightly more carbon dioxide than accorded with the contraction in volume. But the quantities were so slight as to be within the probable limits of experimental error.

[a] U.S. Geol. Survey Bull. 383 p. 30.

The rapidity with which the coals absorbed oxygen may be seen from the data on coals 43 (Sheridan, Wyo.) and 49 (Benton, Ill.) in table 1, which show that in less than 15 days these coals had exhausted the oxygen from a volume of air equal to their own volume. In neither of these instances was the volume of carbon dioxide formed during the process greater than one-tenth of the volume of oxygen absorbed. That oxygen is probably taken into chemical combination rather than occluded or adsorbed by coal was shown by a simple experiment with the Benton, Ill., coal (No. 49). After being supplied with oxygen for five months, during which time it combined with oxygen equal in volume to nearly seven times its own volume of oxygen, a sample of the coal was placed in boiling water in a flask. The gases evolved during 15 minutes' boiling showed no excess of oxygen over that contained in air.

LOSS OF HEATING VALUE.

The largest volume of combustible gas evolved was from the sample of Benton, Ill., coal. From 12.2 kilograms of this coal, 16.9 liters of methane were evolved in one year and five months. If a calorific value for methane of 9,400 small calories per liter is assumed, there were lost by the 12.2 kilograms of coal $9,400 \times 16.9 = 158,860$ calories. As the heating value of the coal was about 7,500 calories, the percentage of loss was approximately $\frac{158,860}{12,200 \times 7,500} = 0.16$ per cent. It is evident, therefore, that no considerable loss of heating value can be attributed directly to the escape of combustible gases from coal during storage at ordinary temperature.

CONCLUSIONS.

The results of the experiments discussed in this paper show that certain American coals, whose mining is attended with danger from accumulations of inflammable

gas, liberate this gas not only while they are being broken down in mining, but also during a long period thereafter. At first the gas escapes rapidly, but the rate diminishes and tends toward a final cessation in 3 to 18 months. If the volume of the small lumps of coal used in the experiments be taken as the unit of measurement, about one-fourth volume of methane escapes during the crushing of the coal, as shown by Chamberlin, and one-half to one and one-half volumes on continued exposure to the air, as shown by the authors. The loss of fuel value by this loss of gas is small, but the danger of accumulation of explosive gas from this source in mines and in coal bunkers is sufficient to justify its being taken into account in the ventilation of mines and in the storage of coal.

PUBLICATIONS ON FUEL TESTING.

The following publications can be obtained free of cost by applying to the Director of the Bureau of Mines, Washington, D. C.:

BULLETIN 1. The volatile matter of coal, by H. C. Porter and F. K. Ovitz. 1910. 56 pp. 1 pl.

BULLETIN 2. North Dakota lignite as a fuel for power-plant boilers, by D. T. Randall and Henry Kreisinger. 1910. 42 pp., 1 pl.

BULLETIN 3. The coke industry of the United States as related to the foundry, by Richard Moldenke. 1910. 32 pp.

BULLETIN 4. Features of producer-gas power-plant development in Europe, by R. H. Fernald. 1910.

BULLETIN 5. Washing and coking tests of coal at the fuel-testing plant, Denver, Colo., July 1, 1908, to June 30, 1909, by A. W. Belden, G. R. Delameter, J. W. Groves, and K. M. Way. 1910. 62 pp.

BULLETIN 7. Essential factor in the formation of producer gas, by J. K. Clements, H. Adams, and C. H. Haskins. 1911.

BULLETIN 8. The flow of heat through furnace walls, by W. T. Ray and Henry Kreisinger. 1911.

BULLETIN 9. Recent development of the producer-gas plant in the United States, R. H. Fernald. 1909. 82 pp., 2 pls. Reprint of Bulletin 416.

BULLETIN 11. The purchase of coal by the Government under specifications, by H. Pope. 1911. 80 pp.

TECHNICAL PAPER 1. The sampling of coal in the mine, by Joseph A. Holmes. 1911. 18 p.p.

Technical Paper 9

DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
JOSEPH A. HOLMES DIRECTOR

THE STATUS OF THE GAS PRODUCER AND OF THE INTERNAL-COMBUSTION ENGINE IN THE UTILIZATION OF FUELS

BY

ROBERT HEYWOOD FERNALD

WASHINGTON
GOVERNMENT PRINTING OFFICE
1912

THE STATUS OF THE GAS PRODUCER AND OF THE INTERNAL-COMBUSTION ENGINE IN THE UTILIZATION OF FUELS.

By ROBERT HEYWOOD FERNALD.

INTRODUCTION

Investigations into the possibility of generating producer gas for power purposes in a commercial way from the various mineral fuels of the country have been carried on for some time by the United States Government. These investigations have been associated with steaming, briquetting, coking, and other tests, all of which supplemented an examination into the nature, extent and distribution of the fuels used. The tests have been made with carefully selected representative samples and carload lots of coal, lignite, etc. procured especially for the purpose by experienced collectors.

The investigations promise to yield a highly important result—the development of greater efficiency in the use of all fuels. This result is of especial importance for States remote from coal supplies.

In New England, for example, marked economies can be gained by a general use of the gas producer, and moreover these economies would be sufficient to overcome the handicap placed on industries there by the transportation charges on coal. The development of power in the New England States through the efficient method suggested by these investigations would mean a yearly saving of many millions of dollars.

Many States of the West that have no good coal are also greatly benefited by the investigations, which have shown the adaptability of the gas producer for the utiliza-

tion of low-grade coal, lignite, peat, etc. As mined, these fuels cannot be used in boiler furnaces and will not bear long transportation, but the gas producer makes them of potential value. Thus the gas producer is an agency of conservation. It helps to keep the low-grade coals from being permanently lost by being left in the mines in such condition as to make their future recovery impossible. In States in which deposits of low-grade coal, lignite, and peat are found, the present cost of power, as developed in steam plants with coal that has been shipped a considerable distance, can be materially reduced by placing producer plants at the mines or bogs, so as to utilize these low-grade fuels without cost of shipment by generating electric current which can be easily transmitted to desired points within a wide radius.

NATURE OF TESTS.

The tests that have been conducted at the Government fuel-testing plants are of two classes. (1) those made with the pressure-producer installation used at St. Louis, Mo., and Norfolk, Va., between October 1, 1904, and June 30, 1908, and (2) those made with the down-draft producer plant installed at the Bureau of Mines experiment station in Pittsburgh, Pa., between July 1, 1908, and June 30, 1910. The problems taken up at the Pittsburgh station involved new apparatus and a method of procedure totally different from that followed at St. Louis and Norfolk.

A somewhat detailed account of the producer-gas investigations of the Government from October 1, 1904, to June 30, 1910, is given in Bulletin 13[a] recently issued by the Bureau of Mines. The more important facts and conclusions presented in that bulletin by C.D. Smith and myself are summarized in this paper, which is issued mainly for distribution to persons who may not care for the more detailed technical statements contained in Bulletin 13.

* * * *

CHEMICAL ENGINEERING SERIES

Coal, Coke, and Coal Chemicals

BY

PHILIP J. WILSON, JR., PH.D.
Research Associate, Carnegie-Illinois Steel Corporation
Formerly Senior Fellow, Carnegie-Illinois Steel Corporation Fellowship, Mellon Institute

AND

JOSEPH H. WELLS, PH.D.
Senior Fellow, Carnegie-Illinois Steel Corporation Fellowship, Mellon Institute

FIRST EDITION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK TORONTO LONDON
1950

Volatile Matter. The volatile matter represents that portion of a coal which is converted into volatile products when the coal is heated in the absence of air. Because the proportion thus vaporized varies with temperature and time of heating, for comparative results the conditions of the test are standardized and are rigidly adhered to. A 1-g sample of the dry coal in a weighed, covered platinum crucible is heated for exactly 1 min at 950 + 20°C (1742 + 36°F). The loss in weight times 100 equals the percentage of volatile matter.

The concentration of volatile matter ranges from about 2 to 8 percent in anthracites, and up to over 40 percent in some American bituminous coals. It is a very important value to consumers of coal. High-volatile coals, for instance, tend to burn with a long flame and may give much smoke. In order to secure maximum thermal efficiency during combustion, the volatile matter must be completely burned; the coal, therefore, requires careful firing or is burned on grates designed for its combustion. Steam coals containing a relatively low volatile content, 15 to 25 percent, have often been preferred because they tend to give less smoke. Powdered coal for boiler firing is preferably high in volatile matter, although low-volatile coals have also been used satisfactorily in this form. The gases evolved from the powdered coal aid in rapid combustion. On account of the high yields of gas obtainable from high-volatile coals, they are preferred for the manufacture of coal gas. The importance of the volatile matter in byproduct coking is discussed in Chaps. 7 and 8.

Ash. The ash is determined by complete combustion in excess air of a weighed sample of the coal. From the weight of noncombustible residue the percentage of ash is calculated. Coals range in ash content from 2 to very high percentages. The following figures show the range in ash content of the coals from three important btiuminous fields in the United States:

	Percent by weight
Pennsylvania	5-12
Illinois, Indiana	7-17
Oklahoma	6-11

Coal ash is derived from clay, iron pyrites, limestone, sand, and other mineral matter, all in a more or less finely divided form distributed throughout the coal in the seam; clay, shale, or slate from the floor, the roof of the seam, or veins in the coal mass; and the inherent inorganic matter chemically combined with the organic matter of the coal. Although the ash in coals in the United States varies widely in chemical composition, it usually comes within typical percentage limits, as follows: [1]

* * * *

[1] W. A. Selvig and F. H. Gibson, *U.S. Bur. Mines, Tech. Paper* 679, 1945, 20 pp.

Established 1845

SCIENTIFIC
AMERICAN

March 1974 Volume 230 Number 3

The Gasification of Coal

This formerly widespread technology, which lost its markets to natural gas and petroleum, is now being reexamined. New methods promise an alternative source of fossil-fuel energy

by Harry Perry

Nearly every major city in the eastern U.S. once had its gashouse, where gas was manufactured (usually from coal) for lighting and cooking. The gashouses and the bulky cylindrical storage tanks that stood near them gradually disappeared after World War II as natural gas came to be distributed nationally by pipeline. Now, with both natural gas and petroleum increasingly in short supply, the idea of improving the nation's energy situation by the gasification of coal, which is plentiful, is attracting much interest.

Coal is found in 30 of the 50 states and represents more than 90 percent of the proved reserves of all developed fuels. At the 1972 rate of consumption the proved coal reserves would not be exhausted for some 600 years. Even if coal were the sole source of energy and the total demand for energy rose at the rate of 3.5 percent per year, the proved reserves would last for 47 years and total coal reserves for nearly 75 years.

Natural gas gained its ascendancy because its cost is low and its heating value is high. Like other gas it is clean, easy to distribute and convenient to use. In the years after World War II it therefore became the preferred residential and commercial fuel and also found many industrial applications. For these reasons the consumption of natural gas grew at a rate of 5.4 percent per year between 1947 and 1971, compared with a rate of 3.1 percent per year for the total energy consumption.

Gas made from coal could substitute for natural gas, although the old technology of coal gasification would have to be improved in order to give the product the heating value of natural gas (about 1,030 British thermal units per cubic foot). In addition the unenriched gas made from coal (with heating values of from 125 to 560 B.t.u. per cubic foot) would serve well in a number of industrial applications. It is therefore not surprising that the gasification of coal is being reexamined as a major source of clean energy from domestic resources.

Gas manufactured from coal was first produced in the late 18th century by heating coal in the absence of air. (It was heated by burning part of the coal outside a vessel containing the remainder of the coal; if the coal inside the vessel had been allowed to come in contact with air, it would have burned, forming combustion-product gases rather than gas that could itself be burned later.) The first coal-gas company, which distributed its product for lighting, was chartered in London in 1812; the first U.S. company was chartered in Baltimore in 1816.

In those days the gas was being produced by destructive distillation, that is, by heating the coal to a temperature where it decomposed chemically. The gas produced by the distillation of coal has a heating value of from 475 to 560 B.t.u. per cubic foot, depending on the type of coal and the temperature to which it is heated. A similar type of gas is produced when coal is carbonized to manufacture coke; frequently coke-oven gas supplemented coal gas when it was locally available and coal gas was in short supply.

In these processes 70 percent or more of the original coal remains as a solid residue, consisting mostly of carbon, that must be sold or otherwise utilized. With coke-

oven gas this is no problem, since coke is the major product. With coal the answer lies in going a step beyond distillation to gasification.

Gasification involves not only heating the coal, as in distillation, but also the subsequent reaction of the solid residue with air, oxygen, steam or various mixtures of them. The distillation step releases a certain amount of gas that has a fairly high B.t.u. content because methane (CH_4) and other higher hydrocarbons contained in the coal are among the first components to emerge as the coal decomposes. The gasification step produces a gas that is essentially a mixture of hydrocarbon and carbon monoxide (which has a much lower heating value than the distillation gases do) with some of the gases distilled from the coal. The amount of the distilled gas in the final product varies with the gasification process.

Oxygen is expensive, and so the old gas companies resorted to an alternative process to make a gas that supplemented coal gas and coke-oven gas. The process produced what was known as "blue gas" or "water gas." Anthracite coal from which the fine sizes had been removed, with the large sizes being crushed to an acceptable dimension, was fed to a vessel lined with a refractory material. After the gasifer had been brought up to a suitable temperature the coal (it could also be coke) was blasted with a stream of air and heated further by combustion with oxygen in the air. During the first part of this "blow" period the gas produced was mostly dioxide ($C + O_2 = CO_2$), but as the coal or coke in the upper level of the bed grew hotter the reverse reaction ($CO_2 + C = 2CO$) began to go, meaning that carbon monoxide was being produced in increasing amounts. After enough coal or coke had been heated sufficiently the valves controlling the flow of air were closed and other valves were opened to begin the "run" period, in which the hot coal or coke was reacted with steam ($C + H_2O = H_2 + CO$). It was a cyclical process, leading to complications in the design and operation of the equipment.

The water gas had a heating value of about 300 B.t.u. per cubic foot compared with the value of from 475 to 560 of coal gas, so that it had to be enriched. The enrichment entailed another cyclical process. The gas made at the end of a run period was hot and contained enough carbon monoxide so that it could be burned to heat refractory bricks enclosed in a "carburettor" vessel. When the bricks were hot enough, the heating gas was shut off and oil was sprayed on the bricks, where the heat caused the oil to be cracked into lighter hydrocarbon products. The resulting gas, which had a high heating value, was mixed with the gas made during the run period to produce what was known as "carburetted blue gas."

The companies originally sold a coal gas with a heating value of about 550 B.t.u. per cubic foot. Burners were therefore designed to handle a gas of that quality. With burner designs fixed, manufactured gas, no matter how it was produced, was usually adjusted to that heating value. On the introduction of natural gas it became necessary in some areas to produce a gas that could be mixed with natural gas. Fortunately the heating value of the carburetted gas could be controlled to a large extent by adjusting the type and quantity of oil sprayed on the refractory bricks.

Then there was "producer gas," which was even cheaper than carburetted water gas. It had a heating value of from 110 to 160 B.t.u. per cubic foot, which meant that it could not be widely distributed because the cost would be prohibitive. (Distribution costs account for much of the consumer's bill; even with natural gas the distribution costs in the District of Columbia represent 65 percent of the total delivered cost.) Producer gas served well, however, in industries that required a clean fuel for combustion purposes or a source of heat for manufacturing processes and that could make the gas locally, so that the cost of distribution was small.

Producer gas was made in a continuous process wherein a bed of hot coal or coke was blasted with air or a mix-

ture of steam and air. The final product necessarily contained nitrogen from the air and carbon dioxide resulting from the combustion of carbon with oxygen. The carbon dioxide could be removed, but the nitrogen diluted the heating value of the gas. This disadvantage was unimportant when the gas was burned as an industrial fuel but made it unsuitable as a synthesis gas (hydrogen and mixtures of hydrogen and carbon monoxide employed in making plastics, synthetic fuels and other synthetic products) and for distribution by utility companies.

Starting in about 1850 and continuing until World War II, the technology of making water gas and producer gas was improved steadily in the U.S. After manufactured gas lost its markets in the U.S. the technology was further improved in Europe, where coal was then the only indigenous fuel found in any significant quantity. New processes were investigated, taking advantage of technical advances in other fields such as the development of large-scale oxygen plants, new methods of handling solids in reactions with gas and improved construction materials. At about the time the technology had reached a stage where plants could be installed, however, natural gas was discovered in the North Sea and in North Africa. In addition most of the European nations decided to shift from an economy based on high-cost indigenous coal to one based on what was at the time low-cost imported petroleum. Few coal gasification plants embodying new technology were installed, and interest in further improving the technology flagged.

The two processes that were installed most often in Europe and elsewhere were the Lurgi fixed-bed pressurized gasifier and the Koppers-Totzek fully entrained, atmospheric gasifier. Both types served mainly to make synthesis gas for the manufacture of ammonia and other synthetic products, although in some places Lurgi plants made a gas that was distributed as city gas. Neither of these processes meets all the qualifications of an ideal

gasification scheme. An ideal process would be a single-stage, continuous operation employing air as the oxidizing medium; it would convert any type of coal into a combustible gas or a synthesis gas that was low in inert constituents.

Although both the Lurgi process and the Koppers-Totzek process are single-stage and continuous, they both rely on oxygen rather than air as the oxidizing medium. The Lurgi gasifier is pressurized, which for most applications of synthesis gas is an economic advantage over processes operating at atmospheric pressure. On the other hand, the Lurgi process requires a sized coal (fines must be removed) and a noncoking or weakly coking coal (because if the bed of coal cokes during gasification, it forms a solid mass that prevents the passage of gas through the bed and brings gasification to a halt), whereas the Koppers-Totzek process will function with any coal.

In the U.S. the renewed interest in coal gasification to produce a substitute for natural gas has led to serious consideration of installing Lurgi or Koppers-Totzek plants. Neither process, however, yields a gas that could substitute for natural gas because it does not have the heating value or the composition required. The gas resulting from each process is basically a mixture of carbon monoxide and hydrogen, plus a certain amount of methane distilled from the coal during heating. Carbon monoxide and hydrogen both have a heating value of 300 B.t.u. per cubic foot—far below the heating value of natural gas. Moreover, local gas companies would not be allowed to distribute such mixtures (although they once were) because carbon monoxide is poisonous and hydrogen is difficult to contain and also has burning characteristics that would require special burners.

Both processes could, however, make a raw synthesis gas that (after purification) could be methanated to yield a gas suitable as a substitute for natural gas. Methanation involves passing the gas over a special nickel catalyst

to convert it into almost pure methane, which is what natural gas is. So far, however, the methanation step has not been demonstrated on a commercial scale.

[Steps in Coal Gasification Chart Omitted]

Although research in the U.S. on coal gasification is now centered on making a low-cost synthesis gas from which a substitute for natural gas can be produced, in the near future coal gasification will also be employed to provide the raw material for the manufacture of other synthetics (alcohols, ketones, waxes and all types of petroleum products) and for the hydrogen required to produce synthetic liquid fuels from coal. The ratio of carbon to hydrogen is much higher in coal than in oil, coal liquefaction involves producing hydrogen from coal by a gasification process and reacting it with coal so as to increase the hydrogen content of the coal and produce an oil.)

In addition new regulations on the emission of sulfur oxides and the difficulties that have been encountered with stack-scrubbing processes have led to a renewal of interest in producing a low-B.t.u., low-sulfur gas from coal to be burned as a boiler fuel. Most of the early research and development on sulfur oxide control was centered on removing sulfur oxide from the Blue gases resulting from the combustion of coal. All the stack-scrubbing processes tested are reported to have been too unreliable for the sustained performance required for utility and industrial boilers, and the costs are much higher than originally anticipated. Two particularly troublesome problems are the large volume of gas that must be treated (making the cost of removal high) and the disposal in an ecologically acceptable manner of the solid waste material that is formed.

If coal is first gasified with air to form a low-B.t.u. gas, the resulting hydrogen sulfide can be removed by proved methods before the gas is burned in the boiler. The volume of raw gas to be treated would be less than half what

must be handled when sulfur oxide is removed from flue gas, and no environmentally troublesome by-product would be created. Interest in low-B.t.u. gasification as a means to the control of sulfur oxides has been further stimulated by the possibility that the more advanced processes being developed for producing high-B.t.u. gas could be modified for making low-B.t.u. gas.

Several new methods of coal gasification are being investigated, and two have reached the demonstration stage. Since most of the research has been directed toward producing a substitute for natural gas, all the processes have attempted to retain in the product gas as much as possible of the methane that is released during the early part of the process, when the coal is simply being heated. In this way the overall capital cost and the material requirements per unit of methane are reduced. Retaining methane is also advantageous when a low-B.t.u. boiler gas is made, because the methane makes for a lower cost and a higher quality.

The basic steps required to produce a synthetic natural gas from coal can be described in general terms [*see illustration on preceding page*]. First the coal is prepared, which entails crushing it to the desired top size, removing fines (if necessary) and extraneous material and drying the coal (if necessary for the subsequent steps). The coal is then either sent to the gasifier or, if it is a coking coal and the process cannot operate with such a coal, pretreated with heat to destroy its coking properties.

The coal is devolatilized, or distilled, either in the gasifier or in a separate vessel. As many of the distillation products as possible are retained to reduce the overall cost of gasification. Since these gases are distilled from the coal during the early part of the process and react more readily with either pure oxygen or the oxygen in the air than the char that is also produced does, the objective of retaining the distilled gases in the finished product requires special provisions to ensure that the gases do not

come in contact with the oxygen and steam put into the system subsequently.

[Hygas Process Chart Omitted]

For making high-B.t.u. gas most of the processes call for steam, oxygen and either coal or char as the feed materials. The oxygen reacts with part of the carbon to provide heat and raise the temperature high enough for the balance of the carbon to react rapidly with steam to produce a mixture of carbon monoxide and oxygen. If one wanted to substitute air for oxygen in order to avoid the expense of oxygen, the nitrogen in the air would dilute the product gas; therefore certain processes resort to a heat carrier as the means of providing heat. An inorganic material is heated in a separate vessel, with air as the oxidant. The material is then put into the gasifier, where it raises the temperature to the level required for the char or the coal to react with steam.

[Carbon Dioxide Acceptor Process Chart Omitted]

In making hydrogen, synthesis gas or high-B.t.u. gas the raw gas is next treated to remove tar and dust and is passed over a shift catalyst, which serves to speed up the reaction in which the four components of the gas (carbon dioxide, hydrogen, carbon monoxide and steam) reach equilibrium ($CO_2 + H_2 = CO + H_2O$). Any desired ratio of carbon monoxide and hydrogen can be achieved by adjusting the amounts of steam and carbon dioxide. When hydrogen is the desired final product, the carbon monoxide is all converted to carbon dioxide and scrubbed from the gas by any of several processes. In making synthesis gas, which figures in the manufacture of a wide range of chemical products, the ratio of carbon monoxide to hydrogen is adjusted to obtain the optimum composition for the chemical to be manufactured.

[Synthetic Process Chart Omitted]

When high-B.t.u. gas is the objective, the appropriate ratio of hydrogen to carbon monoxide is produced. The gas is then purified to remove the sulfur compounds that may be present. The reason is that the catalysts that have been tested for the crucial step of methanation are all nickel-based and are highly sensitive to poisoning by sulfur compounds.

No full-scale commercial methanation plant has yet been built. A test is under way, however, at a Lurgi plant operated by the Scottish Gas Board. The test, which started last fall and is being conducted by a consortium of American firms, will use 10 million cubic feet per day of purified Lurgi gas to demonstrate the efficiency of various methanation catalysts and the amount of cleaning that must be done to keep the catalyst functioning for an acceptable period of time. A second major engineering problem is the rapid removal of heat released by the highly exothermic reaction; if the heat is not removed, it can cause deterioration of the catalyst through sintering or the deposition of carbon.

A major alternative in making high-B.t.u. gas is to gasify part of the coal to form hydrogen and then to produce methane by the reaction of hydrogen directly with coal or char ($C + 2H_2 = CH_4$). Heat does not have to be supplied, since the reaction is exothermic. The products of the reaction are then methanated to eliminate any residual carbon monoxide and to bring the gas to a heating value acceptable for distribution through pipelines. The major advantages of direct hydrogenation are that it requires fewer materials and has a higher thermal efficiency than complete gasification followed by methanation over a catalyst.

Making a producer gas is a much simpler operation than making a high-B.t.u. gas. Because it requires fewer

steps and employs air rather than oxygen, the cost of making it on a commercial scale should be lower than the cost of making high-B.t.u. gas. After the coal or char has been reacted with air the hot raw gas, containing from 110 to 160 B.t.u. per cubic foot, is treated to remove tar and dust and further treated to remove hydrogen sulfide. The product is a low-B.t.u. gas suitable for boiler fuel. Since a substantial amount of natural gas (34 percent in 1971) is consumed by industry, any substitution of producer gas made from coal would reduce or even eliminate the problems arising from the present short supply of natural gas.

The two new processes that have reached the demonstration-plant stage are the HYGAS process, which is being developed by the Institute of Gas Technology, and the CO_2 Acceptor process, which is a project of the Consolidation Coal Company. Other processes, which are at or approaching the pilot-plant stage, include the BI-GAS process of Bituminous Coal Research, Inc., and the Synthane process of the U.S. Bureau of Mines. All the processes under investigation can be classified in various ways: by the method of supplying heat for the gasification reaction (internal heating or external heating); by the method of achieving contact between the reactants (fixed bed, fluidized bed or entrainment in the gasifying medium); by the flow of reactants (concurrent or countercurrent); by the gasifying medium (hydrogen or steam plus oxygen, air or enriched oxygen), and by the condition of the residue removed (slagging, which means that the residue is liquid ash, or nonslagging, which means that it is dry ash). Nearly all the combinations of ways to gasify coal represented by these classifications have been investigated.

In the absence of full-scale commercial plants the cost of coal gasification can be only roughly estimated, and the estimates must be viewed with caution. In a presentation to the Panel on Coal Gasification of the National

Academy of Sciences representatives of the Lurgi process estimated that as of about the beginning of 1972 the capital cost of a gasifier producing 250 million cubic feet of gas per day would be from $180 million to $190 million. The estimate did not include working capital, interest during construction or start-up expenses; these items would increase the cost to about $250 million, based on 1970 dollars. In the fall of 1973 the El Paso Natural Gas Company estimated the cost of a similar plant at more than $400 million. All the newer processes are estimated to have somewhat lower capital costs than the Lurgi process [*see illustration above*].

[Gasification Costs Chart Omitted]

An entirely different technology that is attracting interest is gasifying coal underground. The idea is not new, and a fair amount of research was done on it in various countries until about 1960. Concern about shortages of energy has focused attention on it again.

Any process would require the creation of enough permeability in the coal so that a stream of air could flow from one point in the seam to another point without undue loss of pressure. The coal could then be ignited at either end and gasification would begin. Part of the coal would burn with the injected air, producing a mixture of carbon monoxide, carbon dioxide and heat. If good contact between gas and solid could be maintained, the hot carbon dioxide would then be reduced to carbon monoxide by a reaction with the hot coal. The product would be a producer gas.

Experiments in underground gasification of coal have created the required permeability by a number of methods that entail digging shafts or by one or another variation of the percolation methods, in which two holes are drilled from the surface to the coal seam and then connected so that air can flow between them. The experiments have

been able to produce a combustible gas, but they do not do so continuously and the gas does not have a constant heating value. Most of the tests have resulted in poor recovery of the available coal and have failed to achieve the level of control of the solid-gas contact that is required to produce consistently a gas of high quality. Many other problems, such as subsidence of land and contamination from ground water, have not been solved.

A number of new approaches have been proposed. They include breaking up the coal with explosives and linking boreholes by drilling with lasers. If a successful method could be developed, the energy from coal in the ground could be extracted with little or no requirement for underground manpower. Moreover, it might be possible to extract the energy from coal seams that are too thick, too thin or too poor in quality to be exploited by conventional methods.

COAL HANDBOOK

Edited by
ROBERT A. MYERS

TRW Energy Systems Group
Redondo Beach, California

MARCEL DEKKER, INC.
New York and Basel

* * * *

II. CLASSIFICATION OF COAL BY RANK

Coal deposits were formed from plant materials by the action of heat acting through long periods of time, supplemented by the effect of pressure. The first stage of coalification involves the formation of peat, then lignite, followed by subbituminous coal, bituminous coal, and finally anthracite. Plants and trees contain about 50% water and have a *dry-basis* heat content of about 8000 to 9000 Btu/lb.[1] The chemical composition of the plant kingdom consists mainly of varying ratios of the multi-ring highly oxygenated organic compounds cellulose and lignin. The coalification process can be regarded as a progressive elimination of oxygen in the form of carbon dioxide and water, such that the concentration of carbon in the remaining material increases. Thus, the 30 to 50% dry mineral-matter-free oxygen content found in plant material progressively reduces to 20 to 25% for lignite, 10 to 20% for subbituminous coal, 5 to 10% for bituminous, and to as low as 1% for anthracite. There is a concurrent increase in mineral-matter-free heat content from 4000 to 4500 Btu/lb for plant materials to near 15,000 Btu/lb for some bituminous and anthracite coals.

Classification of coal by rank as presently utilized in the United States is shown in Table 1, together with ultimate analysis carbon/hydrogen/oxygen ratios for the various ranks. The American Society for Testing and Materials (ATSM) ranking system classifies coal according to fixed carbon or volatile matter for medium-volatile bituminous through anthracite coals, on the basis of both fixed carbon and heat content for high-volatile A bituminous coals and on the basis of heat content for lignite through high-volatile B bituminous coal. The British National Coal Board has established a ranking system based on coal volatile matter and coking properties and there is

TABLE 1 Classification of Coals by Rank

Class	ASTM classification method: Limits of fixed carbon[a] (% w/w)	Limits of heat content[a] Btu/lb)	Carbon	Hydrogen	Oxygen
I. Anthracite	86-98	-	90-97	3-5	1-3
II. Bituminous			85-90	4-5	5-10
low-volatile	68-86	-			
medium-volatile	69-78	-	-		
high-voltaile A	<69	< 14,000			
high-volatile B		13-14,000			
high-volatile C		11,500-13,000			
III. Subbituminous		8,300-11,500	75-85	5	10-20
IV. Lignitic		6,300-8,300	70-75	4-5	20-25
(Plants & trees)	25-30	4,000-5,000 [1]	50-60	5-6	35-40

[a] Mineral-matter-free (mmf) basis. To convert to MJ/kg, multiply by 0.00232.

[b] Dry mineral-matter-free (dmmf) basis, normalized for exclusion of sulfur and nitrogen.

an international system of coal classification based on volatile matter, heat content, and coal coking properties.[2]

III. PHYSICAL AND CHEMICAL STRUCTURE

To the naked eye, coal appears to be a compact stratified material. It is chemically and physically complex, having a physical microstructure that is discernibly derived from plants, and a chemical structure containing a wide variety of polymeric organic compounds and crystalline minerals.

The structure of coal is presented visually in the following section beginning with photographs of features visible to the naked eye and apparent to the touch, and progressing in ever-smaller dimensions through fossilized plant structures discernible in two-dimensional perspective by optical microscopy (10^{-4} to 10^{-6} m) and in three dimensions by the electron microscope (10^{-6} to 10^{-7} m or 10,000

to 1000 A), culminating in a model representation of the molecular structure of the coal organic matrix (atomic and molecular features a few angstroms in size). The chemical structure of coal will be built up starting with the elemental composition, arrangement of the elements as molecules, and molecules as a polymeric and crystalline continuum.

A. Visual Properties

Coal petrography is based on the macroscopic and microscopic appearance of coal as well as secondary differentiations made on the basis of coal hardness and density. It is these latter properties that allow mechanical separation of visibly differentiated coal components.

1. Macroscopic Properties

Blocks of bituminous coal are shown in Fig. 1 as seen by the naked eye. Certain structural features are at once evident. Brilliant shiny bands can be seen as a single 3-cm-thick layer (labeled V) or as thin 2 to 5-mm sheets alternating with bands of dull appearance (labeled C—the combined effect is a bright look). A less regular area of gray (labeled D) is also seen as well as a charcoal-like region (labeled F) in the top portion of Fig. 1a. Coal petrography begins here, in the consideration and identification of the composition of these and other structural features. These regions are termed "lithotypes." The brilliant shiny band is vitrain, the gray area is durain, the bright region is clarain (alternating bands of vitrain and durain), and the charcoal-like area is fusain.

This block of coal, and coal in general, can be crushed and the fragments separated by lithotype. The vitrain fragments are very shiny, clean to the touch, and if equal force has been applied, noticeably smaller in size than either durain or clarain. The durain fragments are dull gray in color, and the largest in particle size, as durain is the hardest lithotype. The fusain material is soft and char-

coal-like and crushes to a fine-grained powder that soils the hands if picked up. The term "durain" is often used for dull coal and the term "fusain" for fossil charcoal.

FIG. 1 Photographs of bituminous coal; scale bar, 5×10^{-2} m: (a) fusain (F), vitrain (V), and clarain (C) lithotypes; (b) clarain (C) and durain (D) lithotypes. [Courtesy of R. J. Helfinstine and R. D. Harvey, Illinois Geological Survey, Urbana, Ill.] [Omitted]

TABLE 2 Coal Petrographic Classification [3]

	Megascopic	Microscopic
Rock type	Appearance	Dominant maceral groups
Simple vitrain	Brilliant black luster, very friable into small cubes, clean to the touch	Vitrinite
fusain	Charcoal-like, very friable into soiling black powder, difficult to wet	Inertinite
Complex clairain	Bright with alternating bands of vitrain (brilliant) and durain (dull), fairly friable	Vitrinite and exinite
durain	Dull gray color, very hard, difficult to crush	Inertinite and exinite

2. *Microscopic Properties*

When the lithotypes are polished, etched, or cut into thin sections and viewed in an optical microscope at magnifications of roughly 50 to 1000×, a number of microscopic petrographic units can be seen. These are related to the plant origin of coal and are termed "macerals." There are so many types of macerals that three major maceral groups have been designated: vitrinite, exinite, and inertinite. The dominant maceral-group composition

of each macroscopic lithotype discussed above is shown in Table 2.

Relatively high magnification photomicrographs of a thin section of bituminous coal are shown in Fig. 2. Figure 2a, taken in transmitted light, shows the three maceral groups. The black irregular shaped lenses (mainly upper left) are inertinite. The finely laminated and global material (center) is vitrinite. The globule is about 15×10^{-6} m thick. The white lenticular particles (largest are at the bottom) are exinite. The small elliptical white spots ($1\text{-}3 \times 10^{-6}$ m in diameter) are holes in the thin section where particles of pyrite and quartz occurred but were plucked out of the coal during preparation of the specimen. Figure 2b was taken in reflected light and is of the same specimen section. The detailed structure of the vitrinite (the gray matrix of the photograph) is not resolved in reflected light, but the structure of the inertinite and exinite particles are most evident by this method of examination. Inertinite appears white (mainly upper left) and exinite is dark gray (largest segment at the bottom) under reflected light.

Individual macerals have been found to have significant density differences. For coals of the same rank, the density of macerals decreases in the order: fusinite, micrinite, vitrinite, exinite [4]. Maceral densities for specific ranges of carbon content are shown in Table 3. Thus, macerals can be concentrated, according to specific gravity, into components enriched in specific macerals by various float-sink separation techniques.

FIG. 2 Photomicrographs of a polished thin section of Davis Member bituminous coal from southern Illinois; scale bar, 40×10^{-6} m: (a) taken with transmitted light (I, inertinite; V, vitrinite; E, exinite); (b) taken with reflected light. [Courtesy of R. J. Helfinstine and R. D. Harvey, Illinois Geological Survey, Urbana, Ill.] [Omitted]

TABLE 3 Some Properties of Macerals

	[a](calc)	Carbon content (%)	Reference
Vitrinite	1.3	84-89	5
Fusinite (inertinite)	1.5	92-95	6
Exinite	1.2-1.3	86-89	5
Micrinite (inertinite)	1.4	87-90	5

Scanning electron microscopy (SEM) offers a way to view three-dimensional microscopic details that are thousands or even hundreds of angstroms in size (10^{-7} to 10^{-8} m). Many important coal microstructural features, such as cellular components and cell-contained mineral microcrystals, can be viewed in this way. These units are only two to three orders of magnitude larger than the organic molecules making up the coal molecular structure.

A SEM view of the top of a fresh fracture of a high-volatile C bituminous coal sample is shown in Fig. 3a at $30 \times$ magnification. The coalified (carbonized) plant fibers run from left to right.

A side view of the stacked fiibers looking into the fiber openings is shown in Fig. 3b. The scale bar measures 20×10^{-6} or 200,000 A. It can be seen that the cell walls are on the order of 20,000 A thick, while pore openings of 500,000 A in radius are ubiquitous and openings as small as 50,000 A in radius can be seen clearly. These pores are relatively large compared to pore radii identified in adsorption studies, which vary from 75,000 to less than 20 A [7]. The cell structure is seen to be compressed and distorted in the region shown in Fig. 4a with little pore structure remaining. A fresh fracture surface of coalified plant debris is shown in Fig. 4b. Some possible pore openings can be seen in the middle right section of the figure with radii of 1/10 to 1/100 of the scale bar or 1000 to 10,000 A.

Pores of radii 1000 to 75,000 Angstroms as shown in Figs. 3b and 4b total roughly one-third to two-thirds of the pore volume of bituminous coals, while the total porosity volume generally centers around 10% of the coal volume [7,8].

The intimate association of minerals in coal with the organic coal matrix is shown in Fig. 5a, where deposits of micrometer-size pyrite crystals can be seen within the coalified plant fiber. A closer look at some pyrite mineral matter is shown in Fig. 5b, where individual pyrite crystals and a spherical crystal assembly (known as a framboid) are seen.

B. Chemical Structure

The major elemental components of coal are carbon, hydrogen, and oxygen; the minor elements include sulfur, silicon, nitrogen, aluminium, iron, calcium, magnesium, potassium, sodium, and titanium. Essentially all of the remaining elements occurring in the earth's crust have either been identified in trace amounts or are likely to be present in coal. Carbon is by far the most abundant.

* * * *

III. ELEMENTS OF CLEANING PROCESSES

Although the direct objectives of present coal-cleaning practices are the reduction and control, within predetermined limits, of size, moisture, ash, and, sometimes, sulfur, the properties of coal that have a direct bearing on whether, and how, coal should be cleaned are wider than this list suggests. Thus, the rank of a coal (rank being a complex property descriptive of the nature of the coal substance but not of its impurities) can play a very important role in determining the feasibility and the extent of cleaning.

A. Composition and Rank

Pure coal consists mainly of carbon (C), with lesser quantities of hydrogen, oxygen, nitrogen, and sulfur (H, O, N, S). Compounds of these elements provide the combustible material that constitutes coal's value as a fuel, as measured by the calorific (higher heating) value. These compounds are contained in an organic matrix said to consist of "macerals," to identify them from inorganic materials, which are usually present as impurities assembled in various crystalline matrices termed "minerals." Except for minute quantities of silicon, calcium, and magnesium associated with vegetal material, virtually all other elements found in a coal, other than C, H, O, N, and S, will be associated with the mineral impurities.

When coal is burned, the whole of the macerals present are converted to gaseous combustion products and the mineral impurities present remain as an ignited residue termed "ash." It is important to observe that ash is not the mineral matter originally present in the coal, but the residue remaining after those minerals have been heated to high temperature in air, so that, for example, carbonates initially present will have decomposed and lost carbon dioxide; and pyrites will have oxidized, losing sulfur as sulfur oxides to the products of combustion, leaving iron oxides as a constituent of the ash. Changes resulting from decomposition of the mineral matter in this manner do not make any contribution to the calorific value of the coal, usually detract from it, and where calorific values must be measured accurately, require corrections of the measured values. However, these corrections are not large and it is sufficient for practical purposes to take the ash content, which is easily and rapidly determined, as a direct measure of the mineral impurities present in a coal.

In coalification, or the metamorphosis of vegetal materials to coals, which is generally recognized to follow the sequence peat, lignite, subbituminous, bituminous, and

anthracite, significant changes in the relative proportions of C, H, O, N, and S occurs, the chief of which is the increase in C and the elimination of some H, O, N, and S as large volumes of methane and carbon dioxide are released. Where coals are pyrolyzed, this process is continued by virtually complete elimination of H and O. The carbon residue that remains, however, still contains small quantities of N and S. Typical values for C, H, pyrolyzable matter (volatiles), and residual carbon (fixed) of the various classes of coals are shown in Table 6. This table provides the basis of a system for describing coal rank, which increases as one proceeds down the table. Increasing rank is associated with decreasing volatile matter and increasing calorific value. There are a number of systems of classification.

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GEOLOGY AND COAL-BED METHANE RESOURCES OF THE NORTHERN SAN JUAN BASIN, COLORADO AND NEW MEXICO

EDITED BY:

JAMES E. FASSETT

PUBLISHED BY:

ROCKY MOUNTAIN ASSOCIATION OF GEOLOGISTS
DENVER, COLORADO

1988

Completing, Equipping, and Operating Fruitland Formation Coal-Bed Methane Wells in the San Juan Basin, New Mexico and Colorado

William F. Clark [1]
and
Tom Hemler [2]

ABSTRACT

This paper is a review of drilling, completing, equipping and producing procedures used by operators in the San Juan Basin for Fruitland Formation coal-bed methane wells. Drilling fluids for both open- and cased-hole completions are compared as well as perforating and stimulating techniques. Coal-gas wells have special problems requiring design modifications of production equipment. Artificial lift methods such as the pump jack, gas lift, and progressive cavity pumps, which are in operation on Fruitland coal wells are discussed. Water disposal is a major problem for most Fruitland coal wells. Three disposal methods, evaporative units, evaporative pits, and disposal wells are evaluated. Finally, engineering challenges like zone identification and well spacing concerns are reviewed.

INTRODUCTION

Even though the first San Juan Basin Fruitland Formation coal-bed methane well was developed over thirty-five years ago, the best completion technique for coal-bed methane wells has still not been clearly established. Completion and operation of Fruitland coal-gas wells begins

1 William Clark, Petroleum Engineer, Blackwood and Nichols Co., Ltd., P. O. Box 1237, Durango, CO 81302

2 Tom Hemler, Geologist, Carbon River Energy, 1725 8th Ave., N., Seattle, WA 98109.

with a decision; to drill and complete to minimize damage or to drill and complete to maximize control, and then repair damage done. This basically translates into choosing between an open-hole completion and a cased-hole completion of the coal zones and is a matter of cost versus return.

An open-hole completion assumes a larger hole, gravel pack or liners, less controlled stimulation, if any, production of coal fines, and perhaps a high incidence of clean-out and other workovers. Cased completions assume a smaller hole, perforations, controlled stimulations to bypass formation damage, minimal coal-fines production, and moderate clean-out and repair workovers. This paper has been prepared to assist operators who must answer questions like: Should the completion be open or cased hole?, What kinds of drilling fluids will be required?, Should the well be completed natural or should it be stimulated? In addition, current production equipment design and artificial lift methods for coal-gas wells are reviewed. Engineering challenges such as water disposal and well spacing are outlined in the final sections. Although not intended to be a highly technical analysis, this paper presents a discussion of past and current operating procedures. We have not concluded that there is a best way to develop Fruitland coal-gas wells, but we have outlined some of the problems encountered by experienced operators.

OPEN-HOLE COMPLETIONS

Defined as "no cement on the formation", open-hole coal-bed methane wells have proven so far to be the best producers. Typically, 7-inch or larger casing is set above Fruitland Formation coal zones and then some type of fluid is used to drill out. Completing "barefoot" (no casing through the open-hole section) is best suited when dealing with a single coal zone or closely grouped coal zones. When the open-hole well bore penetrates several

coal zones extending over 100 to 300 feet, then some type of liner is usually employed.

Slotted liners and gravel pack completions have been tried on several Fruitland coal-gas wells over the past eight years and they have had mixed results. Back flushing of the pack or liner is usually necessary because of plugging. Coal fines, which have a wide range of size, easily bridge in the gravel or liner slots and can severely restrict the flow of gas and water.

Once a liner is installed through the coal zones of interest, it is usually perforated with a high density pattern of 4 to 12 shots per foot. For better control, one operator initiated running liners with predrilled 1 inch holes spaced 12 per foot. Temporary plugs were screwed into the liner's holes while it was being run and set in the well bore. Then the plugs, which extend into the inside of the casing, were milled off. This resulted in a liner with many large perforations at a reasonable cost. In some cases, predrilled or perforated liners set through the coal zones can plug with coal fines. To clean out an open-hole perforated liner plugged by coal fines, one operator washed the holes with water at high rates through a packer-like tool on the tubing. Another technique to clean up a plugged open-hole well is to pump 50 percent quality foam and then flow the well back.

CASED-HOLE COMPLETIONS

Cased completions of Fruitland coal zones are commonly 7-inch, K-55, 23-pound casing set through the coal zones or topset, and secondly 5½-inch, K or J-55, 15.5-pound casing set through and perforated. Wells exist with 4-inch or 4½-inch casing, but they are not common. In situations of low water volumes and low fines production, or in areas of dry-gas production, smaller casing design is both operationally and economically effective. Larger sized casing allows for greater volumes of water and fines

to be pumped. More importantly, perhaps, using larger casing removes any potential limiting-strength factor in stimulation design allowing the operator to frac down the casing. Overall, the decision on casing size is an economic one with 5½-inch casing set in an 8¾-inch or 7⅞-inch hole being most common in cased-through completions; 7-inch casing set in an 8¾-inch hole is very common in topset-completions with liner or with gravel pack. Gas and fluid is produced up the tubing and gas may or may not be produced up the annulus.

Many different cementing systems have been used on Fruitland coal-gas wells with varying degrees of success and cost effectiveness. To minimize formation damage, light-weight cements were achieved with nitrogen foam or glass bubbles added to the slurries. Separation problems and occasionally stimulation problems were encountered when light-weight cements were used. A typical cement for a Fruitland coal-gas well would be 50/50 Pozmix with 2 percent gel, 10 percent Calseal (gypsum), and usually some gilsonite for lost circulation control with a weight of 13.5 to 14.0 pounds per gallon.

If an operator elects to do a case-hole completion of a Fruitland coal-gas well, then some care and expense should be part of the design to protect the permeability of the cleat systems that naturally occur in the coal zones. Cement and drilling mud invasion should be a concern. It has not adequately been demonstrated that a chemical interaction between cementing fluids and the coals occur, but it has been suggested that clay in the Fruitland coals does swell in the presence of water.

DRILLING FLUIDS

Determining what fluid to expose the coal zones to is a major decision for an operator. Drilling fluids are selected to control formation pressures and to minimize formation damage during drilling and completion operations. In-

creasing the complexity of this decision is the stability of the coal zones when exposed to different hydrostatic pressures.

Perhaps similar to unconsolidated sandstone formations, coal zones usually flow coal fines when subjected to a low hydrostatic pressure. Drilling through the coal zones with natural gas, air, or air-mist, typically causes an intense flow of coal fines in the returns. Large chunks of coal, up to several inches in diameter, have been observed. Some operators complete their wells this way knowing their coal zones are significantly washed out or perhaps even a cavern has been formed.

In contrast, some operators maintain a high hydrostatic pressure to limit the flow of coal fines. Typically a gel mud, polymer mud, or heavy salt-fluid is used. It has not been clearly established which technique protects the permeability of the natural cleat system best.

Correctly weighted gel or polymer type muds provide good pressure control and hole cleaning capabilities with a strong possibility of formation damage. Whereas heavy fluids containing zinc chloride or magnesium chloride provide good pressure control and minimize formation damage. However, heavy fluids are quite expensive and somewhat difficult to work with because of their corrosive nature.

A typical mud program for cased-hole wells consists of either a gel- or starch-based mud, or a low solids non-dispersed system to the top of the Fruitland. To drill through the coal zones, the mud weight is usually increased to 10 pounds per gallon or higher, depending upon the geologic location. If the coal zones in an area are known to be primarily gas saturated, then a higher mud weight is required compared to an area where the coal zones are primarily water saturated.

Increasing the mud weight just before drilling into the Fruitland permits maximizing the penetration rate and

should provide adequate protection from blow-outs. Great care must be taken to avoid an excessively overbalanced condition. Overweighted mud could permanently seal the natural permeability of the coal zones which would also seriously affect stimulation behavior. Some operators add potassium chloride to their mud systems to lessen the possibility of formation damage from the mud filtrate.

Completing a Fruitland coal-gas well open hole is usually done to reduce formation damage as much as economically feasible. Table 1, a drilling fluid comparison, presents the general relationship of pressure control, potential for formation damage, and expense. These factors need to be balanced to determine the best operating procedures for drilling and competing wells.

Table 1. Drilling fluid comparison.

Fluid	Pressure control	Formation damage	Expense
1) Weighted mud	Good	Possible	Moderate
2) Heavy fluids	Good	Unlikely	High
3) Produced water	Fair-good	Unlikely	Low
4) Natural gas or air	Poor	Unlikely	Moderate
5) Air mist	Poor	Unlikely	Moderate
6) Foam	Fair-good	Unlikely	Moderate-high

Air-mist or stiff foam have been used as alternative drilling fluids to mud, air, or natural gas. It is usually difficult to control formation pressures with air-mist fluid during drilling and completion. While foams can control the pressures, the cost generally exceeds that of muds. Foam has also been used to clean out open-hole wells which were plugged or bridged with coal fines.

Certain operators have been fairly successful using produced coal-formation water to drill and complete open-hole coal-bed methane wells. Continuously pumping produced water or alternating between water and gas down the drill string causes the well to flow in a heading manner, unloading slugs of gas, water, and coal fines. This

well bore flushing technique tends to keep the coal fines in upward motion.

Produced water is also used to circulate out sand and coal fines after a cased-hole well has been stimulated. Once the hole is clean, rods and a pump are installed and the well is put on production. Produced water is popular in both cased- and open-hole completions because it will not damage the formation and it is inexpensive.

Overpressured Fruitland coal-gas wells are capable of unloading a column of produced water. Well control is achieved by maintaining back pressure with a snubbing unit. When actually drilling or cleaning out the well bore, back pressure is not maintained. The snubbing unit enables the operator to hold back pressure on the well during bit trips or while running a liner.

When using fluids like natural gas or air for drilling and completing operations, the formation will frequently flow massive slugs of coal fines. In this situation the field personnel should be advised not to sharply over pull the drill-string weight. Such an action could cause the coal fines to bridge or pack around the drill string. It is better to keep the drill string rotating while only pulling up 5 to 10 points (thousands of pounds), then slack off and repeat until the drill string is free. This method of keeping the bit down in the flow has prevented numerous fishing jobs.

PERFORATING

Given a cased completion and the presence of some fluid used during drilling, two simulation plans need to be considered to open the formation: 1) A perforating plan that allows maximum stimulation and clean up; and 2) A perforating plan that allows maximum productivity of the formation. Perhaps the most common technique is four jet shots per foot (JSPF) over the entire coal zone with hole sizes of 0.38 to 0.50 inches. Usually there is some separation between the coals and the top of the

Pictured Cliffs Sandstone. The intent is: 1) To provide maximum surface area for production which minimizes damage from drilling; 2) Maximize formation control in terms of fines and pressures; and 3) To allow controlled stimulations.

In wells that have a single thick coal zone (20 feet or greater), some operators have gone to a limited-entry approach of 2 JSPF over part of the total zone. This approach is somewhat cheaper and may be as effective as 4 JSPF in achieving effective stimulations. Available data is limited, but does suggest that high break-down pressures can be encountered in both scenarios. Factors such as acidization, time before stimulation, and fracturing strength of the coal could be more significant than the number of perforations.

Casing slotting which is used in the Black Warrior Basin, has not become popular in the San Juan Basin. This is perhaps due to the cost of slotting or to the effectiveness of other perforating techniques. Slotting in terms of stimulation would create a well bore that would behave as an open hole and most likely would limit the overall-treatment effectiveness. Slotting could have value over perforations in naturally-completed wells.

STIMULATION

Given a cased Fruitland coal-bed completion, stimulation is almost a necessity, and occasionally should be considered for open-hole completions. Stimulations typically use cross-linked gelled water or 70 percent nitrogen foam. Non-propped fracs have been tried with both gel and foam. There is no apparent increase in effective permeability associated with either fluid due to the high closure-stresses of the Fruitland coals. Straight water fracs with low sand concentration of up to two pounds per gallon at suitable rates, while not common, appear to be effective and appear to increase effective permeability.

At this time, a very common stimulation is a cross-linked gelled water frac at rates above 30 barrels per minute (BPM) and greater than 50,000 pounds of 10/20- or 12/20-mesh sands; volumes of 100,000 gallons and 100,000 pounds are quite common in thick zones. The intent is to create a wide vertical fracture of as great a length as possible, perhaps at concentration of 6 pounds per gallon or higher. Break-down pressures can be quite variable. Foam is a more expensive medium that generally requires higher horsepower for injection of comparable volumes. It is unclear as to whether there is a difference in effectiveness of foam and cross-linked gelled water jobs. The tendency towards larger jobs and even massive hydraulic fracs of 400,000 pounds or more of sand suggests that gelled water-jobs are becoming the most common stimulation. Massive fracs that stay vertical appear to be more effective in creating frac length, but the resulting increased gas-production rates may not be enough to be cost effective.

At larger volumes of higher pressure the tendency to flow back sand can be very pronounced, and at least one operator has gone to resin-coated sands to seal the area around the well bore, preventing flow back and preserving permeability. This is an operational and economic decision dependent upon volumes and pressures anticipated.

Stimulation in open-hole completions in thick coal zones and multiple coal zones tend to be less effective in that they enter only parts of zones or single zones and flow back excessive fines and sands regardless of fluid and sand volumes. Open-hole completions result in much less control of the formation than is necessary for multiple completions and production operations.

PRODUCTION EQUIPMENT

Regardless of the type of completion, Fruitland coal-gas wells are usually troublesome to produce because of coal fines. Completed coal zones can be unstable resulting in production of various-sized coal fines in conjunction with the production of methane-gas and water. Coal fines, ranging in size from dust to chunks, create problems which require some design modifications to typical oil field production equipment.

Design considerations and field operation of wellheads, separators, filters, dehydrators, and evaporative units are discussed in the following sections. This summary is based on personal experience and conversations with equipment manufacturing representatives, production engineers, and field personnel.

Wellheads

Fruitland coal-bed methane wells in the San Juan Basin are typically overpressured. In the northern part of the San Juan Basin numerous drill-stem tests and producing wells indicate a pressure range for the Fruitland from 108 percent to 140 percent of hydrostatic pressure (K. C. Bowman, written communication). These percentages translate into surface shut-in pressures of 1,400 to 1,700 pounds per square inch gauge (psig).

Wellheads with a 2,000 psig rating are acceptable, however, a 3,000 psig rating is recommended to handle the abrasive of the coal fines when moderate flow rates are expected. Some operators who have high-volume wells (2 to 4 million CFPD and (or) 1,000 to 2,000 BWTD3, use 5,000 psig-rated wellhead equipment.

Flow lines are typically 2-inch, however, for high volume wells, 3-inch flowlines are necessary and schedule 80 pipe is desirable to provide some protection against abrasion. Full-operating ball valves for flow control will be less likely to plug or cut out.

Separators

Gravity separation, production equipment's best friend, has trouble dealing with coal fines. Microscope-sized coal

dust stays entrained in the gas stream and must be filtered out. Large pieces or chunks of coal, ⅛ inch to 1 inch or greater, frequently plug or cause malfunctions in the separator's liquid dump valves and other controllers. Medium-sized coal fines usually are gas saturated and float at the gas-water interface in the separator requiring extra setting time.

Determining the best method to deal with the Fruitland's pressure is a primary element in surface-equipment design. If one elects to use standard-rated production separators with a maximum working pressure of 1,000 psig, then pressure control is necessary. Pneumatic motor valves controlled by a pressure-sensing element provides the necessary flow control for safe operations.

When working with 2-inch flow control valves the frequency of plugging can be high. Motor valve trim, seat, and (or) stem, can erode quickly with high flow rates and (or) coal-fine production. Keeping a separator's safety controls in working order can be a challenge. Use of 3-inch flow control valves results in less plugging, however the expense can be significant. The initial cost of a 3-inch motor valve is five to eight times higher than the 2-inch model and replacement parts follow suit.

Experience obtained from operating pressure-control equipment on coal-gas-well separators has caused some operators to increase the maximum working-pressure rating on their units. It is approximately 25 percent more expensive for a separator with a 1,440-psig rating than the 1,000-psig standard model. Increasing the maximum working pressure to 1,700 psig causes a price hike of 35 percent over the standard model. However, higher initial costs can be offset through lower maintenance expense and less downtime for repairs. These factors combined with the increased safety margin makes the higher-pressure-rated approach worth considering.

Most Fruitland coal-gas wells produce gas, water, and coal fines requiring two-phase operators. Because the gas-

to-liquid ratios on these wells are usually low, vertical separators work best. Also, flowing Fruitland coal-gas wells tend to produce in a heading or slugging manner and a vertical separator should have large liquid capacity to handle this.

In the event a Fruitland well makes some condensate or oil, a two stage separator is recommended. A high-pressure vessel separates the gas from the liquids and then a low-pressure vessel separates the oil from the water. Condensate from Fruitland completions and commingled Fruitland-Pictured Cliffs completions is usually high in paraffin content which requires special handling, such as heaters in the stock tanks.

There are many factors to consider when sizing a separator for a Fruitland coal well: Obviously the production rate of gas and water are important, however other factors such as slug capacity, retention time, and operating pressures play a significant role in design. Floating coal fines in the water phase requires additional retention time for separation. Increasing the retention time from 1 minute (typical for oil separators with non-foaming conditions) to 3 minutes, decreases the liquid capacity by 67 percent.

Overall, it is recommended that a coal separator be sized with conventional design parameters and then increased to the next commonly available pipe size. In other words, if a design analysis requires a 20-inch-diameter by 10-foot-long vessel, then the size should be increased to a 24-inch by 10-foot size. If a 24-inch diameter is calculated then use 30-inch pipe. Optionally, increasing the length of the vessel also provides an economical way to achieve greater capacity, particularly when designing for high maximum working pressures. Once the initial gas head from a Fruitland well is produced, usually fairly quickly, warm formation water, 70 to 80 degrees F at the surface, prevents any freezing problems. A water bath around half of the separator vessel provides sufficient heat.

Multiple-pass flow coils in a heater water bath are usually not necessary.

Separator control equipment, when exposed to coal fines and slug flow, can malfunction. A backup system for the liquid level controller and dump valve will decrease operating problems. A secondary-level controller mounted above the primary controller with the output signal sent to both the primary and secondary dump motor valves is good insurance to prevent liquid carry over.

Motor valves which dump the separator's liquid should have large trim to prevent plugging. Also snap action is preferred over throttling because of the coal fines. Some operators are using a motor valve designed for paper mill slurries that has a rotating ball action. A preferred design would have a full-opening isolation valve upstream of the liquid dump valve for convenient maintenance.

Conventional mist-extractors in coal-gas-well separators can plug with coal fines. This problem is decreased by installing a vein-type mist extractor followed by a conventional wire-mesh type. One design permits the mist extractor to be back flushed through a mounted nozzle system. If plugging is a severe problem then the increased expense of a removable head is justified.

Filtration Units

Small coal fines in the gas stream and separated-water system require filtration. Produced gas from the separator should go through a cartridge-type filter to prevent downstream problems in the dehydrator, compressor, and (or) meter. Filtration of produced water is usually required to prevent damage to a disposal well.

Gas filters can be free standing units with sufficient working pressure rating. Once separator design incorporates the filter in the separator's water bath to prevent freezing and to allow for convenient maintenance. Replacement frequency of the filter cartridges depends on a

coal-gas well's average production of fines and the occurrence of liquid carrying over from the separator.

Competency of filters can be stated in nominal or absolute terms. An absolute filter is rated to stop all particles larger than the specified size, that is, a 10 micron absolute filter stops all particles larger than 10 microns in size. A nominal competence is an arbitrary rating determined by the manufacturer based on the weight percent of removed particles. A test of a 1-micron nominally rated filter showed that no 1-micron-sized particles were stopped, while particles up to 50 microns were passed.

San Juan Basin operators working with Fruitland coal-gas wells are using 20- or 25-micron nominal filters for gas. Produced water is cleaned up with 10-micron absolute or 2-micron nominal filters before it is injected into a disposal well. Filtration procedures increase the cost of operating coal-gas wells but this should be recouped through less downtime.

Dehydrators

Dehydration of coal-bed methane is the same as conventional glycol-based systems developed for gas wells. Design parameters that might be different are maximum operating pressure, inlet gas temperature, and carbon dioxide content. Glycol absorption of water vapor works best at low gas temperatures (65 to 70 degrees) and higher operating pressures.

In the preceding discussion of separator design, pressure-control alternatives were outlined. If the production-facility design specifies that the separator is to handle pressure control, then a standard 1,000 psig, maximum-working pressure dehydrator unit would be appropriate. In a design case where the separator has no pressure control, the dehydrator design should incorporate pressure control to protect the gathering facilities in a worst-case scenario.

Use of a compressor on a coal-gas well for gas-lift operations or for lowering the wellhead pressure can significantly increase the flowing temperature of the gas. Glycol-absorption efficiency decreases as the temperature increases. An overall analysis of production mechanics will insure that the maximum water content allowed by the gas-purchase contract will not be exceeded.

Another topic in most gas-purchase contracts is the maximum allowed level of carbon dioxide in the produced gas. Coal-gas wells produce varying amounts of carbon dioxide and treatment facilities are sometimes necessary. If the gas analysis shows more than 10 percent carbon dioxide, then the use of some stainless steel elements in the dehydrator should be considered.

Evaporative Units

There are several evaporative units in service on San Juan Basin Fruitland coal-gas wells. Basically, evaporative units boil produced water which releases steam to the atmosphere and concentrates the salts in the residual fluid. Handling produced water through an evaporative unit is expensive and has several operational problems. However, in some cases it may be the best alternative for an operator.

Cost of an evaporative unit depends on the size: approximate costs are: 20 barrels of water per day (BWPD) unit—$5,000; 50 BWPD unit—$8,000; 100 BWPD unit—$12,000. Fuel usage and maintenance costs depend on several factors and the following discussion is general in nature. Metering of consumed fuel gas used by evaporative units averages 0.600 MCF to vaporize one barrel of water; at a price of $2.00 per MCF, the fuel cost is $1.20 per barrel of water evaporated.

Operating an evaporative or steamer unit can be very expensive and time consuming. The buildup of mineral deposits on the fire tube and walls of the containing vessel

significantly decreases efficiency and can cause control equipment to malfunction. Solutions to these problems include: 1) A time controlled flushing cycle to remove all or most of the residual fluid; 2) An aeration system to agitate the bottom of the vessel before draining off the residual fluid; 3) A holding tank in which the water is preheated with steam before entry into the evaporating vessel; 4) Dual float control valves to shut down the burner; and 5) A regular washing program to clean the vessel's interior.

Several of the approximately twenty evaporators built and used in the San Juan Basin have malfunctioned, requiring major repair work. Collapsed fire tubes, melted floats, and other disabling events have occurred. Regular inspection and a good maintenance program is clearly necessary.

Total operational cost of evaporative units is estimated to be $2.00 to $3.00 per barrel of water evaporated when capital, maintenance, and fuel expense are considered. For wells with remote locations and water production less than 100 BWPD, preferably less than 20 BWPD, an evaporative unit is probably the most economic choice.

Disposition of the residual fluid is a potential problem because of its high total dissolved solids (TDS). This fluid ranges from 100,000 to 300,000 parts per million TDS at discharge temperature depending on the flushing program. The volume of produced water is reduced approximately 90 percent by the evaporative unit. Trucking the reduced volume of residual fluid to a disposal site is more efficient; however the solid-mineral precipitates may require special handling.

ARTIFICIAL LIFT

Most Fruitland coal-bed methane wells are not capable of continuous fluid flow, resulting in the need for some type of artificial lift. Methods currently employed include sucker-rod pumps, cavity-type pumps, and gas lift systems.

These artificial-lift methods are discussed primarily from an operational point of view. Limited data prevents an analysis of the average lifting cost of each method.

Pump Jack

The most common lift equipment is a sucker-rod pump with pumping units of 160, 300, and 640 size (peak torque rating) and 64- to 200-inch stroke lengths. Water productivity knowledge or estimates are necessary to configure a pumping system capable of pulling down the fluid level to the Fruitland. A ring type plunger pump, with a tolerance for solids, placed in the tubing at or below the producing formation has proven cost effective by minimizing plunger wear and maximizing sustained pumping. A sloppy pump with undersized pump rings results in a tolerance for solids without significantly decreasing efficiency. A fairly common assembly would be a stainless steel plunger with undersized plasic rings.

Some accommodation for gas locking through a gas anchor, charger valve, or equalizer valve may be necessary along with proper pump spacing. The size of the plunger depends upon the water volumes. Common sizes are 1.75- or 2.0-inch plungers. Ring-type plunger pumps with properly sized pumping units and sufficient stroke are capable of pumping 2,500 BWPD. More common are units capable of pumping 600 BWPD or less.

Fruitland coal wells equipped for sucker-rod pumping have a somewhat established workover pattern. Wells in the early phase of production need workovers for problems related to abrasion caused by sand and coal fines working on plungers, barrels, and valves. It is fairly common for pumping coal-gas wells to have two or more workovers in the first year.

In the later phase of more stable production (when the gas/water ratio has increased) workovers are more typical of gas wells. These workovers usually involve rod and

tubing wear and more pump repair due to abrasion. Long-term problems such as scaling, corrosion, and rod and pump wear, mark the final phase of production; usually when the coal-gas wells are significantly dewatered. The use of sloppy pumps with cased completions has proven effective in minimizing workover frequency as have gravel packs and certain types of liners in open-hole completions. However, high volume producers might expect two workovers in the first year and one workover every two years after that for the first five years of well life.

Cavity Type Pumps

As an alternative to sucker-rod pumping, the progressive-cavity pump is currently being field tested on several Fruitland coal-gas wells. These pumps are highly tolerant of solids, and the turning of the rods in the tubing usually does not create excessive tubing wear. However, in the presence of high volumes of gassy fluid and deviated holes, tubing and pump wear can be excessive.

Under normal operating conditions, the ring-type plunger pump and the progressive-cavity pump are very comparable. Initial cost of a progressive pump system is significantly cheaper, approximately 70 percent of the cost of a beam-pumping unit for a well 3,000 feet deep. The rotor turning within the stator in a progressive-cavity pump, especially where high gas volumes are present, can create too much friction causing stator burnout and (or) excessive pump wear. Careful placement of the pump below the perforations or the deepest coal zone may reduce the problem.

Changing the rotation frequency of the rod string allows the cavity pump to handle a wide range of fluid volumes. Power failure, either electric or gas engine, can cause the coal fines in the tubing to settle and perhaps lock up the rotor. Some operators use a standing valve on the bottom of the tubing to prevent the liquid from falling back.

As more experience is gained with progressive-cavity pumps, they could become as popular as pump-jack systems on water-producing Fruitland coal-gas wells. If electricity is readily available the progressive pump system should be evaluated.

Gas Lift

Though not as popular as pump jacks, gas-lift systems are currently in operation on several Fruitland coal-gas wells in the San Juan Basin. Most of these installations are single-well systems where produced gas is recirculated to keep the well flowing. Conventional gas-lift systems usually involve a packer and gas-lift valves installed on the tubing.

"Poor boy" gas lift eliminates the gas-lift valves and packer. Compressed gas flows into the casing annulus, and then enters the bottom of the open ended tubing, to help the formation gas lift the water to the surface. This approach works fairly well on strong wells which are capable of unloading themselves. For the marginal wells, unloading by swabbing may be necessary to establish continuous flow. Operational problems with the compressor or other production equipment may cause the well flow to stop. This possibly is the biggest disadvantage of the poor boy approach.

A fluid-filled well can be unloaded with a packer and as lift valves and a suitable compressor. However, a temporary gas supply may be needed. Once steady tubing flow is achieved then either the casing pressure or the flowing tubing pressure is monitored. When the monitored pressure is above the desired level then a motor valve allows the excess or produced gas to flow into the sales line. Maintaining the casing pressure and flow up the tubing is the first duty of the recirculated compressed gas with any excess being sold in a controlled manner.

When dealing with high-volume wells or excessive coal-fine production, it is at times desirable to circulate gas

down the tubing. The larger tubing-casing annulus would be less likely to plug. Another gas-lift technique is the casing-lift system which is based on annular flow. Gas lift valves flow compressed gas from the tubing into the annulus. This would be particularly useful in completions where the coal zones are 100 to 200 feet apart, and a packer above the uppermost perforation is less likely to keep the lower zones producing.

Recirculating gas-lift systems are initially cheaper than a comparable beam-pumping system. There are no pumps to wear out or rods to pull, therefore workover expenses should be significantly less. If gas-lift valves are installed in a well, it is recommended that the bottom valve be wire-line retrievable for maintenance and performance optimization. Most operators need more experience with gas-lift systems to determine the cost effectiveness for use on coal-gas wells.

WATER DISPOSAL

Disposal of produced water is the largest single operational problem and cost encountered in Fruitland coal-bed methane development. Fruitland coal-gas wells in the San Juan Basin produce water in a wide range of amounts; some wells make less than 10 BWPD and a few wells make more than 2,000 BWPD. Coal-gas wells usually produce higher volumes of water initially with water volumes decreasing over time. This diminishing water production results in changing water disposal requirements over well lives. Produced water needs to be handled and disposed of in accordance with relevant Federal, State, and Tribal regulations.

There are many water-disposal methods available and the following is a discussion of evaporative pits and disposal wells. Evaporative units (see Production Equipment section) are in some cases a reasonable disposal technique. Produced water from Fruitland coal-gas wells ranges in composition from fresh to 20,000 parts-per-

million TDS. Coal water contains predominantly sodium bicarbonate which disassociates into sodium and bicarbonate. These compounds form scale and can create land use problems.

Evaporative Pits

Initial coal-water disposal efforts in the San Juan Basin centered on evaporative pits sized to handle produced volumes of several wells based on the evaporation rate with seasonal storage adjustments. Historically, a 1- to 2-acre pit is capable of handling several hundred to approximately 1,000 barrels of water per day with year round evaporation.

The cost of an evaporative pit including purchase of surface lands as well as a construction and liner costs totals approximately $50,000. Significant operating problems of vandalism, hydrogen sulfide gas pollution, and leakage have occurred. Fencing, bacteriacide treatment, and monitoring can lessen these daily operating problems. When an evaporation pit is abandoned, the concentrated brine and scale require special handling.

Disposal Wells

Disposal wells are an attractive alternative to surface pits in that they minimize vandalism, hydrogen sulfide problems, and do not require large surface-area ownership. Additionally, depending upon the receiving formation, disposal-well capabilities usually far exceed produced water volumes and can continuously operate without seasonal fluctuations. However, disposal wells can cost as much or more than a producing well, depending on the depth and need for stimulation.

Water-disposal wells have been completed in many formations from the Tertiary Ojo Alamo Sandstone down to the Jurrasic Entrada Sandstone. Existing wells in the San Juan Basin are injecting water into the Ojo Alamo Sandstone, Pictured Cliffs Sandstone, Mesaverde Group,

Morrison Formation and Entrada Sandstone. Capacities range from 500 to 600 BWPD at 600 psig into the Ojo Alamo, to over 10,000 BWPD at 2,500 psig with a cumulative volume of approximately 1,000,000 barrels of water into the Entrada. The tendency of these wells to pressure up over time may be a function of the plugging from fines resulting in decreasing capacity.

Disposal wells must meet mechanical and quality criteria administered either by the Environmental Protection Agency (EPA) or its administering agency within a state. Quality criteria may make certain zones unsuitable for injection because of water incompatibility or the disposal zone's inability to take large volumes of water. Administratively and mechanically the disposal well route may be difficult to pursue, however, it may be the best solution for high-volume disposal.

Disposal into shallow zones such as the Ojo Alamo Sandstone or Farmington Sandstone Member of the Kirtland Shale may be restricted by quality-criteria problems or limited capacities. Although usually capable of accepting high water volumes, deep disposal wells into the Entrada Sandstone are wildcat in nature and are very expensive to drill and complete. Less-deep zones of the Pictured Cliffs sandstone and Mesaverde Group will meet quality and capacity requirements for most operators and may be the most cost effective disposal zones provided these zones are not capable of commercial hydrocarbon production. Stimulation of these shallower zones will usually improve daily capacity at minimal cost.

ENGINEERING CHALLENGES

Determining the best procedures to develop Fruitland coal-bed methane wells is a challenge we all face. Clearly, the Fruitland coals contain a tremendous gas resource and through diligent work the people involved will be able to establish optimum reserves. Both the operators and regu-

latory agencies need to make difficult decisions with limited information to establish proper Fruitland coal-gas development. Two of the challenges are formation identification and well spacing.

Formation Identification

Determining which pool a well's hydrocarbons are coming from can be a problem in some areas of the San Juan Basin because of the intertonguing of the Fruitland Formation and the Pictured Cliffs Sandstone. In areas where the Pictured Cliffs is not capable of commercial production, or when wells are clearly completed only in the Fruitland coals, then zone identification is not a problem. However, some wells completed only in the Pictured Cliffs sandstones, can produce gas having a strong coal-bed methane signature. This could be the result of the stimulation treatment not staying in the intended zone. In other wells there appears to be production of a mixture of coal-bed and sandstone-reservoir gas and water.

Effective reservoir management is difficult in these mixed cases. To be able to keep meaningful production records, correct formation identification is necessary. Pools such as the Los Pinos Fruitland-Pictured Cliffs, South, in northern New Mexico, which are handled as down-hole commingled pool, need to be reevaluated and perhaps redefined.

In some areas of the San Juan Basin, one possible scenario would be for an operator to drill to a specified depth; complete and test the well; and finally present to the regulating agency, information which identifies the well as capable of producing from the Fruitland or the Pictured Cliffs or both. Well spacing and zone identification are integral matters which must be addressed harmoniously to insure the best development.

Well Spacing

Because of the site specific nature of Fruitland permeability, spacing should be flexible enough to allow

down-spacing in the less permeable areas. Spacing-units of 320 acres would appear to be the largest that would not penalize most operators and still allow prudent development in non-unit situations. Unitized operations could include owner-agreements regarding well spacing perhaps as large as 640 acres without penalizing any mineral owner. This large spacing is not reasonable for prudent development of non-unitized lands.

The directional-permeability phenomenon in coal also suggests larger drill-site-spacing blocks; 320 acre-blocks are desirable, with downsizing allowed. The ultimate number of wells will depend upon economic recovery of the maximum amount of gas at minimum cost. The engineering challenge will be to use geologic and engineering data to locate wells in irregular patterns dictated by permeability zones, which vary. Perhaps these zones are influenced by the cleat system and they may change from well to well in a dynamic situation. These factors will require an understanding of the direction and extent of permeability in a field area concurrent with development.

CONCLUSIONS

Completion and operation of Fruitland coal-gas wells begins with a single decision; to drill and complete the well to minimize damage or to drill and complete the well to maximize control and then repair the damage done. An open-hole completion assumes a larger hole, gravel pack or liners, less controlled stimulation, if at all, production of coal fines, and a high incidence of clean-out and other workovers. Pumps and production equipment must be capable of handling the coal fines. Cased completions assume a smaller hole, perforations, controlled stimulations to bypass formation damage, minimal fines production, and limited clean-out and repair workovers.

The use of produced water as a drilling fluid is popular in both cased- and open-hole completions because of low

cost and no damage to the formation. Regardless of completion type, the engineering challenge is to find the best production equipment and operating procedures for each well. Large separators and filtration units are necessary to handle the produced coal fines. Usually there are large volumes of produced water which should be properly disposed of at the cheapest price. Water disposal methods include evaporative units, evaporative pits, and disposal wells. With future Fruitland coal-bed methane development, the need for water disposal will increase and this issue will receive more attention and regulation by State and Federal agencies.

Technical Report

Coal Composition, as Related to the Mode of Occurrence of "Coalbed Methane"

prepared by

Jeffrey R. Levine, Ph.D.
Consulting Geologist
Tuscaloosa, Alabama 35404

for:

Maynes, Bradford, Shipps, and Sheftel
Durango, Colorado

November 9, 1992

WHAT IS COAL?

Definitions of Coal

The term "coal" is loosely applied to a diverse class of organic matter-rich sedimentary materials and can be defined in a variety of ways—stratigraphically, petrographically, geochemically, or otherwise—depending on the context in which it is being considered. Coal eludes a precise definition, even from a scientific perspective, owing largely to its complex and highly variable nature. In spite of any differences among them, however, most published definitions of coal include three unifying elements: 1) coal is a type of sedimentary rock, 2) coal is comprised primarily of carbonaceous material, and 3) coal is readily combustible. Beyond this, coal composition can be quite complex and variable. In the end, coal can be satisfactorily defined only through a detailed description of its composition and structure.

A particular functional definition of coal appears in the American Geological Institute's *Dictionary of Geological Terms* (Bates and Jackson, 1980). This definition is adapted from the definition(s) originally developed by Dr. James M. Schopf of the U.S. Geologic Survey (Schopf, 1956, 1966):

> coal—a readily combustible rock containing more than 50% by weight and more than 70% by volume carbonaceous material, including inherent moisture, formed from compaction and induration of variously altered plant remains similar to those in peat. Differences in kinds of plant materials (type), in the degree of metamorphism (rank), and in the range of impurity (grade) are used in classification.

Important facets of this definition are: 1) There are many different varieties of coal. These may be described and classified according to their type, rank, and grade. 2) Mineral matter is a constituent of coal. Mineral matter content provides the criterion for distinguishing coal from all other types of sedimentary rocks. 3) Coal includes "inherent moisture".

Consistent with this definition, the American Society for Testing and Materials, which establishes North American standards for testing and classifying materials, defines coal as (ASTM, 1991, D-2796-88) "a brown to black combustible sedimentary rock (in the geological sense) composed principally of consolidated and chemically altered plant remains." As a footnote, the definition goes on to state that "coals exhibit a wide range of properties due to differences in the kinds and relative amounts of different plant materials and intermixed mineral matter, the amount of alteration of the plant remains achieved before burial, and especially the degree of physical and chemical alteration after burial . . . The moisture content and the kind, amount, and mode of occurrence of mineral matter also vary greatly." Once again, mineral matter and moisture are specifically identified as constituents of coal. There are no restrictions made as to the composition of the organic constituents of coal.

Mineral matter is a constituent of coal. Although ASTM does not stipulate a maximum mineral matter content for coal, the ASTM definition for "impure coal" (ASTM, 1991, D-2796-88) is "coal having 25 weight % or more, but less than 50 weight %, of ash on the dry basis." As a footnote, the definition goes on to say that "[sedimentary] material . . . having more than 50 weight % ash is properly called coal or carbonaceous shale or siltstone." By implication, the terms coal or impure coal apply only to rocks that yield less than 50 weight % ash. Although many sandstones, shales, or limestones are free of organic components, no coal is entirely free of mineral components. Mineral matter is an integral component of all coals. Although the term "coal" has occasionally been

used to refer solely to the organic fraction of the rock, this usage is inconsistent with U.S. and international standard terminology. Coal containing a large proportion of mineral constituents may be referred to as "impure" coal, "dirty" coal, or "high-ash" coal.

Various minor and trace elements found in coal occur not as minerals, but actually bonded to the organic structure of the coal (Jenkins and Walker, 1978), partly as organic complexes. For examples, detailed study of uraniferous lignite and uranium-bearing coals of the western United States has shown that in some cases, uranium-bearing minerals are present, but that in many other occurrences, "uranium, although not present as a distinct mineral, is closely associated with the organic carbonaceous material" (Denson et al., 1959). Other trace elements in coal having strong "organic affinities" in Western U.S. coals are barium, magnestium, bromine, strontium, beryllium, phosphorus, sodium, and calcium (Palmer, 1983).

"Inherent moisture" is a constituent of coal. For purposes of mining and commerce, water is routinely considered to be a constituent of coal. Federal guidelines published by the Office of Surface Mining (a division of the U.S. Department of Interior) stipulate that tonnages of coal mined and shipped must be calculated with respect to "inherent moisture" content. These regulations define inherent moisture as "moisture that exists as an integral part of the coal seam in its natural state, including water in pores but not that present in macroscopically visible fractures" (emphasis added). Careful past studies have demonstrated that *in situ* moisture contents are very accurately estimated by the Equilibrium Moisture test (Rees et al., 1939). Therefore, this is the test mandated in the OSM regulations as a measure of inherent moisture content. This is also consistent with the definition of coal discussed previously (Bates and Jackson, 1980) which specifically regards moisture as a constituent of coal.

ASTM also regards moisture as an inherent component of coal. According to the ASTM rank classificaiton system, at ranks up to and including high volatile A bituminous, coal classification is done on the basis of BTU yield on a moisture-containing basis (ASTM, 1991, D-388), where moisture content is, once again, determined via the Equilibrium Moisture test (ASTM, 1991, D-1412).

Coal is a "Mixture" of Constituents

As stated by Green et al. (1982), "coal is a composite material consisting of a huge variety of coalified vegetative remnants into which are also mixed various inorganic minerals components." Essentially, coal is a heterogeneous mixture of constituents. The significance of the term "mixture" cannot be overemphasized, as it provides one of the keys to understanding coal composition and structure. In a chemical sense, a "mixture" refers to any combination of two or more substances that are not chemically bound to each other. The term "chemically bound" refers to relatively strong bonds (typically "covalent" or "ionic" bonds) where electrons are shared between adjacent pairs of atoms. A large proportion of the atoms comprising coal are bound together in this way; but on a slightly larger scale, coal represents an intermixture of constituents which are not strongly bonded to one another, but are merely physically intermixed with one another. In addition, there are a variety of weak intermolecular forces, such as "hydrogen bonds" and "van der Waals bonds" that help to hold together as a coherent mass, but these forces are much weaker than covalent bonds.

Some Keys to Understanding Coal Composition

- The term "coal" does not refer to a specific compound, but to a diverse class of sedimentary rocks comprised mostly of organic matter.

- Coal is not a pure compound, but a heterogeneous mixture of different constituents. Compositional heterogeneity occurs at many different scales, from centimeter-scale banding, visible to the unaided eye, to different types of molecules.
- Mineral matter is a natural constituent of all coals, the relative proportion of which is an important parameter of coal composition.
- Water and methane are natural constituents of all coals, the relative concentration of which are important parameters influencing economic value of the coal.
- Coal composition is not constant, but undergoes a continual evolution during its history in response to changing conditions of temperature, pressure, and chemical environment.
- Oil-like and gas-like substances form in coal as natural by-products of coalification. These by-products are partly retained within the coal structure and partly expelled into surrounding strata. The retained portion becomes part of the so-called "molecular fraction" of coal. The expelled portion become oil and gas *sensu stricto*.
- On a molecular scale, coal constitutes a loose aggregation of molecules of varying size and complexity, bound together by several different types of forces, including: covalent bonds (strong), hydrogen bonds (weak), and van der Waals bonds (very weak).

In considering coal as a heterogeneous "mixture" of ingredients, the components of coal can be investigated and classified on several distinct scales of view. At the millimeter scale (10^{-3} m), coal is comprised as a mixture of interbedded "lithotypes." At the micron scale (10^{-6} m), coal is comprised of a mixture of "macerals"; and at the

submicroscopic nanometer scale (10^{-9} m) coal is comprised of an intertangled network of organic molecules, plus other components.

Coal is analogous to concrete in its microscopic structure. When originally deposited, peats (the precursors of coal) comprise loosely compacted masses of vegetal remains. The vegetal remains are not bound together (although they may be intertangled), and the peat may be broken up by hand. During the coalification process, however, the woody material becomes partly solubilized and gelified. At higher rank, in response to increased temperatures and pressures, this gel dehydrates, and the coal develops a physical coherency. The gelified material, which will become vitrinite, functions as the "glue" which binds the coal together, in much the same manner as cement binds concrete together. The liptinite and inertinite macerals and mineral grains function in a similar manner to gravel in concrete lending strength to the mixture. Although all of the macerals and minerals are consolidated in this way into a more-or-less coherent mass, the macerals and minerals tend to maintain their distinct identity and morphology.

The great variety of organic constituents in coal reflect: 1) variability of the biological materials (plants and micro-organisms) and minerals initially contributing to the coal deposit and 2) mechanical and (bio-)chemical changes occurring shortly after deposition. Both factors have varied significantly through geologic time and in response to differences in climatic setting and depositional regime. These differences have produced coal deposits having greatly differing chemical composition and physical properties, yet the single term "coal" encompasses all these many varieties of materials.

The Molecular Constituents Of Coal

Although the fundamental characteristics of coal molecular structure have been known for some time (Van

Krevelen, 1961), research conducted over the past two decades has provided a considerably more detailed picture of coal structure. Older views depicted coal as a three-dimensional polymeric structure interconnected by a network of bridge structures and cross-linkages (Davidson, 1982; Given, 1984; Behar and Vandenbrouke, 1987). This type of model emphasized the role of strong covalent bonds. The polymeric model for coal is still basically valid, but it is now generally recognized that a diverse suite of "smaller"[1] molecules is entrapped within this three dimensional structure, ranging in size and complexity from CH_4, CO_2, and H_2O at the low end to higher molecular weight aromatic substances, including oils, tars, and asphaltenes, at the upper end.

Strong covalent bonds are much less important in binding this mass together than was previously imagined (Brown and Waters, 1966; Green et al., 1982; Larsen and Wei, 1988). Instead, weaker intermolecular forces, including hydrogen bonding and van der Waals bonding are important. This model is best described as a "two-phase" system, comprising a three-dimensional, covalently bonded "macromolecular matrix", plus an entrapped "molecular fraction"[2] (Vahrman, 1972: Davidson, 1982;

[1] There is potentially some confusion in the terminology here relating to size of these entrapped molecules, depending on the frame of reference. From the perspective of the "macromolecular" structure of the coal matrix (which is "huge"!), these entrapped molecules are "small". From the perspective of oil and gas, however, some of these entrapped molecules are quite large.

[2] The term "molecular fraction" is more-or-less equivalent to the term "mobile phase", as used in many other recent scientific papers on coal composition (e.g., Given, 1984; Given et al., 1986: Derbyshire et al., 1989). The term mobile phase is avoided here, however, because it is somewhat misleading. Most of the molecules comprising the mobile phase do not truly form a distinct phase, but dispersed throughout the macromolecular matrix. Nor are the bulk of these molecules truly mobile in the strict sense. Most are entwined, entrapped, or loosely bonded to the coal structure and can be

Given, 1984; Given et al., 1986; Derbyshire et al., 1989; Herod et al., 1991).

A conceptual representation of the two-component model of coal composition is depicted in Fig. 1. Here, the initial subdivision is between organic and inorganic constituents. The organic fraction is further divided into a macromolecular matrix fraction and an (entrapped' molecular fraction. The molecular fraction is further subdivided into two classes: 1) a tightly bound portion, comprised of free molecules that cannot readily migrate through the coal structure, owing to their size, shape, or the cumulative strength of bonding with the matrix, and 2) a "loosely bound" portion, comprised of smaller molecules that can migrate with comparative ease into or out of the coal structure. In this latter category are methane, carbon dioxide, and water, among others. Of these, methane is of particular economic significance as it represents the predominant contributor to the gases produced from coal.

The specific procedure(s) used to distinguish these two classes of coal constituents is not specified in Figure 1, since a wide variety of methods may be used, each one yielding somewhat different results (e.g. vacuum distillation, thermal treatment, solvent extraction, or ^{1}H-NMR spectroscopy). The unifying concept of all such analyses is to differentiate a fraction of coal that is relatively loosely bonded to the coal structure (molecular component) from a fraction that is more strongly bound and, therefore, more resistant to removal by thermal treatment or by solvents (macromolecular matrix component).

freed only by substantially swelling or breaking down the coal structure, as for example, with pyridine. The "mobility" alluded on the term refers to ability to vribate in a high frequency magnetic field (Given, 1984).

Fig. 1—Conceptual classes of coal constituents, including matrix and molecular fractions (Levine, in press). Methane belongs to the loosely bound molecular fraction. [omitted]

According to current state of knowledge, there is little fundamental difference between the manner that the larger molecules are associated with the coal structure and the manner that the smaller molecules are associated with the coal structure. Neither class is covalently bonded, but only the smaller molecules can be readily removed. The larger molecules tend to remain bonded or physically entangled in the network unless acted upon by thermal or strong solvent extraction methods.

The two-component model of coal composition has been proposed in various forms since around the turn of the century (Given, 1984), but has recently gained broad acceptance as providing a structural model that is both realistic and useful in explaining coal behavior. The two-component model provides the key to understanding the evolution of the physical and chemical characteristics of coal during coalification. Virtually every measurable property of coal is best understood in light of this model, including gas sorption capacity, optical properties, liquefaction behavior, and coking characteristics (Green et al., 1982).

It must be borne in mind that neither the molecular component nor the macromolecular matrix component is homogeneous or pure. Moreover, their composition changes significantly during coalification. For example, at low rank the molecular component is dominated by water, at medium rank by oils, tars, and asphaltic materials, and at high rank by methane and water, but there is always a diverse mixture of species present.

Molecular constituents comprise as much as 30-75% of coal, by weight. Estimates of the weight percentage of

molecular fraction present in coal are variable and somewhat uncertain, depending on the analytical method used (Given et al., 1986 and Derbyshire et al., 1989). Moisture contents (which are less ambiguous) decrease dramatically from over 75% in peat to as little as 1% (or less) in high volatile A bituminous coals (Fig. 2). The percentage of organic constitutents removable by solvent extraction is more uncertain, however, and may vary widely for any given coal depending upon the solvent system used. Pyridine extract yields are believed to provide the best estimate of the entrapped molecular fraction (Larsen and Wei, 1988). Pyridine extractables reach a maximum concentration of around 25-35% at around high volatile A bituminous coals, then decrease once again at higher ranks (Van Krevelen, 1961). Fruitland coals underlying much of the Southern Ute Indian reservation are of high volatile A bituminous rank. Beyond this peak, pyridine yields drop to near zero at anthracite rank, but accompanying this change, the accessibility of smaller molecules such as water and methane increases once again, indicating a reopening of the molecular structure. Thus, at all ranks, loosely bonded molecules comprise a substantial proportion of the total weight of the coal.

Water is part of the molecular fraction of coal. Water is sometimes not viewed as a bona fide constituent of coal since it is so readily removed. Nevertheless, inherent moisture shares the same sort of interrelationship (especially involving hydrogen bonding) with coal structure as other so-called "organic" molecular constituents. When moisture is removed, the coal structure collapses and shrinks, and all measurable physical and chemical properties change (Ode, 1963; Green et al., 1982). In high rank coals, changes associated with dehydration are reversible by resaturating the coal with moisture (Stansfield and Gilbart, 1932; Rees et al., 1939) but at low rank they are partly irreversible (Selvig and Ode, 1953). This

irreversibility is apparently related to collapse of the molecular structure and information of new intermolecular bonds within the non-hydrated fraction. Indeed, moisture provides part of the binding forces that helps to hold coal together. When moisture is removed, most low rank coals shrink and crack visibily, and become weak and friable.

"Oil" is part of the molecular fraction of coal. Oil is a naturally occurring earth material comprised of hydrocarbons and related substances that occur in a predominantly liquid state and are mostly soluble in common organic solvents, but are insoluble in water. In contrast, coal is largely insoluble in such solvents as carbon disulfide, carbon tetrachloride, and dichloromethane (methylene chloride). This insolubility led to the concept of coal have a much more complex polymeric structure than oil (Van Krevelen, 1961). It is now widely recognized, however, that coals in the bituminous rank range contain a substantial proportion of solvent extractable constituents that are very oil-like in composition (Vahrman, 1972; Herod et al., 1991). The difficulty in solubilizing these components of coal is now understood to be due to the rigidity of the macromolecular matrix (Green et al., 1982). In the presence of a solvent that relaxes and expands the macromolecular matrix (such as pyridine), a much larger proportion of entrapped molecules can be freed. Many (although not all) of the pyridine extractable materials are common constituents of petroleum, while others are higher molecular weight materials that are more properly termed tars or asphaltic substances (Vahrman, 1972; Herod et al., 1991).

Thermal distillation procedures, such as Rock-Eval pyrolysis can also liberate a small but significant proportion of entrapped oils from coal (Durand and Paratte, 1983; Teichmuller and Durand, 1983). Figure 3 depicts the gas chromatographic analysis of a thermal extract from a Fruitland coal from the Southern Ute Indian reservation. For this analysis, the sample was held at 300°C sufficient time to volatilize those constituents having boiling points lower than this temperature. (This temperature is considered too low to cause thermal breakdown of the macromolecular matrix). The composition of thermal extract looks very much like a crude oil in its composition, although after a couple of years at the surface most of the low molecular weight "light ends" had apparently either escaped or deteriorated from this sample, or were never present.

Table 2 represents data on the composition of the extractable materials removed from coal by methylene chloride. Here, a detailed chromatographic analysis was not performed, but extractables were classified into several broad categories by liquid chromatography. The properties of "oily" constituents removed was around 0.5-1%, of which around 10-15% were n-alkanes, 40-45% aromatics, 20-30% NSOs, and 15-30% asphaltenes.

Over the past five years or so there has been a large volume of papers published on the oil content and oil generative potential of coals. Much of this work has been done from the standpoint of assessing coal as a "source rock" for oil and gas. (This topic is discussed in additional detail in the section on the "origin" of coal and coalbed methane.) The important conclusion of this work from the standpoint of coal bed reservoirs is that coal generates not just methane as a by-product of coalification but a diverse suite of petroleum, tar, and asphaltic materials. These substances remain entrapped for the most part within the coal structure and substantially influence the coals affinity for other small molecular substances such as water and methane.

Methane is part of the molecular fraction of coal. Methane exhibits a similar relationship to coal structure as water, oil, and other components of the molecular fraction. All of these substances occur as molecules that

are not covalently bonded, but are weakly bonded to or entrapped within the coal structure. The polar forces that bind water to the coal structure are much stronger than the weak Van der Waals bonding that holds methane in place. Also, water can bond to itself, owing to its strong dipole moment. As a consequence, water is typically present in coal in much higher concentrations than methane, particularly at low ranks. Nevertheless, water, methane, and oil "compete" with one another for accessibility within the coal structure (as discussed subsequently, in the section on sorption isotherms). To be fully understood, all the molecular components of coal must be regarded as part of a complex multi-component system. Methane is typically not specifically mentioned in most studies of coal extract chemistry; but this is primarily because most of it has escaped from the coal structure prior to analysis, along with water and other readily-removed constituents. From the standpoint of coal chemistry and structure, however, there are no clear criteria for segregating methane from other molecular constituents of coal. This distinction becomes significant only when the coal is subject to "extraction" methods that preferentially remove the methane.

Fig. 2—Compositional evolution of the molecular fraction of coal during coalification. At low ranks, water is the dominant species. At medium rank, occluded hydrocarbons and asphaltic materials are the dominant species. Methane is present at all ranks, but in quantities to small to depict on this diagram. The prominent hydrocarbon peak at medium rank is the "oil window", representing the rank range over which oil is formed, then subsequently destroyed by thermal processes. [Chart omitted.]

Fig. 3—Gas chromatogram of thermal extract (300 °C) for Fruitland Formation coal, Southern Ute Indian Reservation. [Chart omitted.]

Table 2. Compositions of Rock-Eval and Methylene Chloride Extracts. Fruitland coals. Southern Ute Indian Reservation. [Table omitted.]

WHAT IS COALBED METHANE?

Background

Underground coal seams throughout the world contain an enormous quantity of methane (CH_4) and other light hydrocarbon substances occluded within their molecular structure. ("Occluded" is a term in chemistry meaning adsorbed or absorbed in great quantity.) A variety of other small molecular species are also present in coal, such as carbon dioxide (CO_2), nitrogen (N_2) and water (H_2O). For hundreds of years, the presence of these substances was manifested principally through their (unavoidable) release and discharge into underground coal mine workings, where they can pose a serious safety hazard. Methane, when liberated into the coal mine atmosphere, is the principal constituent of "firedamp" (a traditional miners term for combustible mine gases), and is explosive when mixed with air in proportions from 5 to 35% [3]. Another hazardous mine gas, termed "blackdamp", is comprised of carbon dioxide, which can cause asphyxiation if present in sufficient concentrations.

In order to reduce the safety hazards during mining, these gases are diluted to a fraction of 1% concentration with large volumes of air, which is drawn into the mines by fans, then vented to the atmosphere. Over the past two decades, however, new technologies have been developed which enable hydrocarbon gases to be recovered from coal seams in sufficient quantities and with sufficient purity to permit their use as a pipeline-quality gas. Such coal seam gas recovery methods have been successfully undertaken in association with active mining operations

[3] Less than 5%, there is not enough methane to sustain combustion; greater than 35%, there is not enough oxygen. 9% methane in air is the "stoichiometric" ratio for complete combustion.

before, during, and after mining as well as in "virgin" coal seams where no active mining has yet taken place. It is the goal of commercial coal seam degasification projects to produce gas at rates and volumes that render it economically competitive with other more "conventional" sources of natural gas. When coal degasification is done in conjunction with underground mining, however, additional economic incentives may come via reduced ventilation costs, reduced explosion hazard, and reduced equipment down-time. A further incentive for degasification in advance of mining is the reduced contribution of mine methane emissions to the so-called "greenhouse" gases in the atmosphere.

The term "coalbed methane" is somewhat ambiguous in that it is used in two ways. The first is a purely operational definition, where coalbed methane refers to [any] natural gas produced from coal seams. In this sense, the term coalbed methane does not refer to a particular type or composition of gas, but rather to the fact that it originates from a coal bed. The term arose because coal bed gases are typically very rich in methane (as are most natural gases), but a variety of other constituents may be present, including CO_2, N_2, H_2O, C_2H_6, and higher hydrocarbons. In the second sense, "coalbed methane" refers to the specific substance "methane", which is found occluded in high concentrations in most underground coal seams, and which is the principal contributor toward natural gases produced from those coals. In this latter sense, coal bed gas would be considered to be a mixture of "coalbed methane", plus "coalbed ethane", plus "coalbed carbon dioxide", etc.

In fact, the term coalbed methane has been used very loosely in the past, with little consideration given to the fact that many other substances besides methane contribute to the composition of gases liberated from the coal.

How is Coalbed Methane Produced?

Coal contains within its structure a proportion of constituents that can be volatilized by changing the ambient conditions of temperature and pressure[4]. These volatile components can be released either by decreasing the ambient pressure, by increasing the ambient temperature, or a combination of the two. Increasing the temperature aiso increases the rate at which volatile substances are released. Once volatilized, these substances assume the form of a free fluid (either liquid or gas). In this form, they may flow through the coal, assuming that there is a pressure gradient established. (Given a permeable medium, fluids will always flow from high pressure to low.) The gases that are released from coal in this way effectively *become* what is known as "coalbed methane" or "coal bed gas". Prior to their conversion to a gaseous state, they are effectively part of the coal.

The production of natural gas from coal bed reservoirs involves three fundamental elements: 1) drilling and installation of production tubing, 2) completion/stimulation, and 3) pumping. Drilling and installation of production tubing provides an open conduit through which reservoir fluids (typically water plus methane-rich gas) may be conducted to the surface. Completion/stimulation is intended to increase the interface and connectivity between the well bore and the coal bed. This is usually done either by hydraulic fracturing or by "cavitation" method.

Pumping serves two purposes. 1) It maintains a point of low pressure within the coal bed toward which fluids

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[4] A strong distinction is drawn here between the truly "volatile" constituents of coal (H_2O, CH_4, CO_2, etc.) and so-called "volatile matter", which is determined by the ASTM Proximate Analysis (ASTM, 1991, D-3172). ASTM Volatile Matter is released upon heating the coal to 950°C. At such high temperature, the molecular structure of the coal is radically altered and new substances are formed and liberated. In contrast, the volatile constituents alluded to in the present report are not formed *per se*, but are merely released from the coal structure.

will flow and 2) It removes water from the bed so as to allow gases to flow more readily[5]. In their natural state, the fracture networks in San Juan basin coals are usually water-filled. It has been shown, however, that water is essentially absent in some parts of the basin (Decker and Seccombe, 1986; Scott et al., 1991). In either case, when pressure in the bed is reduced, occluded species such as methane migrate out of the microporous coal matrix and into the major fracture network where they join any other fracture-resident fluids already present (Fig. 4). This mixture of fluids is then free to flow down pressure gradient toward the well. For the most part, the gases from coal bed reservoirs don't become migratory until the pressure conditions in the coal bed are altered by drilling, stimulation, pumping. Any water that accumulates the well bore is pumped off and disposed of. The gases are collected, transported, and sold.

Evidence from gas sorption studies suggests that the conduits through which gas molecules pass during diffusion are on the same order of size as the effective diameter of the molecules themselves (ca. 0.5 x 10^{-9} m). Thus, in diffusion, coal behaves as a "molecular sieve", permitting some molecules to pass through its structure, while excluding others. Molecules migrate at different rates, depending on their size, and on the molecular structure of the coal. Methane diffuses readily and higher hydrocarbons more slowly (Sevenster, 1959). Diffusion through coal appears to be an "activated" process, whereby a molecule must surpass a certain minimum activation energy in order to pass through the system (Nandi and Walker, 1966). For this reason, diffusion rates are more rapid at higher temperature, where a larger proportion

[5] There are some coal bed gas wells in the San Juan basin that do not require pumping because they produce essentially no water. These are relatively uncommon, however. Most coal bed wells require that water be pumped off in order to maintain low fluid pressures.

of molecules possess the minimum activation energy required for transport.

"Gas Content" Determinations

One of the principal means of assessing the reservoir potential of any particular coal is through determination of the concentration of occluded gases. This is measured most commonly by recovering a "core sample" by drilling, and quickly placing it in a sealed canister. The quantity of gases liberated during this process is normally termed the "gas content", but is more accurately described by the term "gas yield".

Although the term "gas content" has come into common usage it creates a misleading impression in several respects. The molecular species that are liberated from coal during these tests are not strictly present in the form of a gas, but assume a gaseous state only after diffusing out of the coal miscrostructure. Therefore, the coal does not contain a gas in the strict sense, but rather a component that can become gaseous under certain conditions. Secondly, owing to the effects of activated diffusion (Nandi and Walker, 1975; Sevenster, 1959), the composition and quantity of gases liberated from test cores of coal is dependent upon the experimental conditions at which the tests are run and is to a large degree arbitrary. Traditionally, desorption tests were run at room temperature, and the cores were desorbed to equilibrate with atmospheric pressure (Diamond and Levine, 1981), but these conditions were simply a matter of convenience. Conditions in the reservoir are quite different. When desorption tests are run at reservoir temperatures (ca. 100-120°F for the San Juan basin) desorbed gases are released more quickly and in greater quantities. Also, greater amounts of higher hydrocarbons are liberated (Fig. 5).

Thirdly, because of the inherent slowness of the diffusion process, desorption test procedures can take many months to complete. The term "residual gas" pertains to

potentially volatilizable constituents that remain entrapped within the coal structure even after extended periods (several weeks or months) of desorption (Diamond and Levine, 1981). In one example, a sample of high volatile A coal (Pittsburgh coal bed) has continued to liberate small amounts of methane even after several years of desorption (J. Ulery, U.S. Bureau of Mines, 1991, personal comm.). Deposition rates may be hastened either by heating the specimen to moderate temperatures (ca. 50-120°C), or by grinding the sample up to a fine micron-sized powder in a hermetically sealed ball mill (Diamond and Levine, 1981). The percentage of so-called "residual", or "remaining" gas measured after grinding can be quite significant depending on the coal sample and measurement conditions, and may represent as much as 50% of the total desorbed gases. All coals may be assumed to retain small amounts of methane and other species within their structure days, months, or even years after being subject to surface conditions. The slow, sustained escape of flammable gases poses a substantial safety hazard in silos or in railroad freight cars where coal is stored, as the gases may explode.

Composition of Gases Desorbed from Coal

There are many varieties of coal bed gas. Nevertheless, *most* natural gas from coal beds is comprised mostly of methane—usually in excess of 90% (as is also the case with most "conventional" natural gas). Some coal bed gas is extremely "dry", being comprised of over 98% methane, particularly from high rank coals and in many localities in the eastern U.S.; but coal bed gas can contain in excess of 10% higher hydrocarbons in some localities, particularly in the western U.S. Other commonly occurring components of coal bed gas are CO_2, N_2 and a variable percentage of higher hydrocarbons. In general the BTU yield of most coal bed gas is of pipeline quality, yielding more than 1000 BTU/cf. Normally,

no processing or cleaning is required aside from water separation.

The composition of natural gases desorbed from coal may be determined via desorption tests or from production wells. In the former technique, a sample of coal is recovered from depth below the surface, typically as a core or cuttings, and quickly placed in a hermetically sealed container. The quantity of gases liberated may then be measured. Although desorption tests are commonly used to measure desorbed gas volumes, compositional analysis is not routinely done, owing to the additional expense and nuisance. It has been generally assumed, without proof, that the desorbed gases were comprised of methane. In fact, other substances are liberated during desorption testing.

Another complicating factor is that the composition of desorbed gases changes with time. This is apparently a consequence of the phenomenon of activated diffusion as well as the variable affinity of the coal for different occluded substances. Methane is liberated relatively rapidly, while carbon dioxide and higher hydrocarbons tend to be preferentially retained; consequently, composition changes with time.

An example from the San Juan basin illustrating this variability is provided by a desorption test sample recovered from the GRI #1 observation well, drilled on the Southern Ute Indian reservation (Fig. 5). Here, a diverse suite of gases were liberated with desorption. Methane contents were 60-70% in the initial stages of desorption, but quickly fell to less than 10%. Nitrogen and propane (C_3H_8) were particularly abundant in these samples, but many other gases were desorbed as well.

Production gases. The composition of gases from production wells in the San Juan basin is quite variable. Some parts of the basin produce gases that are quite dry, being comprised of over 98% methane, while some wells

produce gases that are quite "wet"—wherein a waxy condensate at the surface in addition to gas. Some coalbed wells in the San Juan basin actually produce oil. In other areas of the San Juan Basin, CO_2 content of coal bed gas can be greater than 50%, having a very low BTU value.

Figures 6 a & b show a map of the San Juan basin depicting the regional variability in produced gas composition. Gases from the northern and southern portions of the basin tend to be rich in methane. There is, however, a prominent northwest/southeast trending belt that crosses the basin near the Southern Ute Indian Reservation where produced gases contain substantial amounts of higher hydrocarbons. In some wells, higher hydrocarbons account for over 10% of the hydrocarbon production. CO_2 content of production gases and varies regionally.

Fig. 4—Diagram representing the three stages of gas production from coal bed reservoirs. Initially, the fracture network is saturated with water. As gas begins to form, it forms bubbles, but cannot flow until a minimum saturation is reached, then gas flow commences (from Koenig and Bell, 1985).

Fig. 5—Change in desorbed gas composition with time. Coal sample from COAL Site, Southern Ute Indian Reservation (from Mayor et al., 1991). In this sample, methane constituted a relatively small proportion of the total gas, illustrating the misnomer of the term "coalbed methane".

Fig. 6—Regional variability in composition of produced gases from San Juan basin. a) Ratio of methane (C_1) to hydrocarbons C_1 through C_5 (pentane). In some parts of the basin, methane constitutes less than 86% of total hydrocarbon gases. b) Carbon dioxide content sometimes exceeds 10% (from Scott et al., 1991).

Sorption Isotherms

Sorption isotherms are graphs which depict the quantity of methane or other gases that may be accommodated in coal structure under pressure. Sorption isotherms provide important information about the coal bed reservoir. The importance and relevance of sorption isotherms to the present discussion is two-fold: 1) sorption isotherm curves demonstrate quantitatively that far greater amounts of methane (or other gases) are accommodated in coal under pressure than would be possible if the methane were a free gas. This is due to the fact that sorbed within the coal structure (Metcalf et al., 1991), 2) sorption isotherms can be used to quantitively demonstrate the interaction(s) among various components of the molecular fraction of coal. These relationships will be documented in the following discussion.

Methane Sportion Isotherms. For any given coal, methane sorption capacity increases with increasing pressure of the sorbate. This relationship is demonstrated by the methane sorption isotherm depicted in Fig. 7. This curve was measured on a Fruitland coal sample collected at a depth of 3148 ft from GRI Observation Well #1, at the Gas Research Institute's COAL Site (T32N, R10W, Sec. 17), drilled on the Southern Ute Indian Reservation (Mavor et al., 1991). The curve is steep at low pressure, showing that the first sorption sites are readily filled. At higher pressure, the curve flattens out as the coal approaches its maximum saturation. For comparison, the lower line depicts the quantity of methane that would be accommodated as a free gas in a rock having 1% porosity, which is the estimated porosity for this coal under compression (Mavor et al., 1991). According to this estimate, very little of the sorbed gas can be accounted for by absorption into open pores.

Methane Sorption is Influenced by the Presence of Other Sorbates, including Oil and Water. Thomas and Damberger (1976) studied the sorption of gases into coal

structure for coals from the Illinois basin. They explained the regional variability of sorption capacity as relating to the presence or absence of what they termed "low boiling constituents", which formed in the coal as a by-product of coalification. According to this model, the coal micropore structure becomes "plugged" by secondary hydrocarbons formed during maturation. This implies that the oils which formed during coalification, and which remain entrapped within the coal structure along with other coalification by-products, effectively diminish the coal's capacity to sorb gases. Thomas and Damberger tested this hypothesis by thermally extracting the coal. During thermal extraction, anywhere from 4 to 8% of the coal was volatilized, producing a significant increase in surface area.

Thomas and Damberger's study demonstrates that occluded oils and gases effectively "compete" with one another for sorption sites within the coal structure. In fact, the same effect appears to hold for methane as well. This model has been specifically tested for Fruitland coals using samples from the BEA 15-4 well, drilled on the Southern Ute Indian Reservation (Figure 8). The two samples were collected from the same well, within 100 feet of one another, stratigraphically. The rank of the two samples was essentially identical. Nevertheless, the coals differed substantially in the composition of their molecular fraction. The stratigraphically lower coal contained a much higher concentration of waxy oil as revealed by Rock-Eval pyrolysis and solvent (methylene chloride) extract studies (Table 2; Fig. 8b). Accessibility of H_2O and CO_2 to the coal structure was roughly one half that for the less waxy coal. Gas yields from the two coals, measured by desorption testing, showed roughly twice as much gas desorbed from the less waxy coal. Methane sorption capacity was also slightly lower in the waxy coal (Fig. 8). When the two coals were subject to solvent extraction in methylene chloride to remove occluded oil, the sorbate accessibilities of the waxy coal jumped dramatically, indicating that the sites vacated by the extracted material had become accessible to sorption by methane (Fig. 8b).

For any given coal, the capacity for a given gaseous sorbate is diminished by the presence of other gaseous sorbates. It has long been known that water can substantially suppress the methane sorption capacity of coal (Joubert et al., 1974). Recent research at the University of Alabama has demonstrated that the opposite is also true. Methane can reduce the sorption capacity for water. Research conducted at Amoco Production Research laboratories has demonstrated that nitrogen and methane compete for sorption sites in coal (Puri and Yee, 1990; Arri et al., 1992). Competitive sorption behavior of CH_4-CO_2 systems has also been investigated for San Juan basin coals (Olszewski et al., 1992).

While interrelationships are complicated, it is clear that to fully understand sorption behavior, the overall composition of the molecular fraction should be evaluated in its entirety. In other words, it is an inaccurate oversimplification to represent methane as absorbing on a solid porous substrate. The physical reality is that methane is but one component of a complex system.

Fig. 7—Sorption isotherm, measured at 120°F (reservoir temperature), for a coal from the COAL site, Southern Ute Indian Reservation

Fig. 8—Influence of occluded oil in coal on methane sorption capacity for two coal seams from the same core hole, within 100 feet of one another. a) Sorption isotherms for raw and extracted coal; b) Analytical data

IS COALBED METHANE A PART OF COAL?

The short answer to this question is "Yes". This conclusion is based upon information presented throughout this report.

Coal is sometimes regarded as a solid fuel and, of course, gas is gas; but upon closer scrutiny, it becomes apparent that this distinction is fuzzy, and based to some degree on superficial observations. When a sample of coal is removed from the ground or once the conditions in a coal bed are changed, its composition immediately begins to readjust to its new surroundings. Among the processes that are known to occur are: 1) desorption of occluded gases, 2) desiccation (drying), and 3) oxidation. Coals stored in the absence of oxygen will not oxide; and coals stored under water will not dry out; coals stored under methane pressure will not desorb methane. Coals that are kept cold desorb very slowly; and coals that are heated desorb rapidly, and more higher hydrocarbons are released. Thus, the rate and quantity of compositional changes depends entirely on the ambient conditions to which the coal is subjected.

After the coal has re-equilibrated to its new conditions, its composition and physical characteristics will have changed in a slight but measurable way. The coal shrinks slightly during desorption, and substances are lost from the coal structure. This is observed for methane desorption as well as for carbon dioxide, water, etc. If oxidized, oxygen is added to the structure and the weight of the coal increases. As water evaporates from coal, the weight of the coal decreases. The same thing happens during methane desorption, but the weight loss is too small to be of concern for marketing purposes [6]. In the case of water loss, it has been mandated by Federal regulations that the tonnages of mined coal be considered not on an altered, 'as received" basis, but on an "Equilibrium Moisture"-containing basis, which is though to represent *in situ* bed conditions (cf. previous discussion on "Water is part of

[6] Weight loss during methane desorption has been measured directly at the University of Alabama using an electro-microbalance (Levine et al, 1991). Weight changes constitute only a fraction of 1%.

the molecular fraction of coal"). To the author's knowledge, there are no similar regulations that specifically refer to methane, ethane, carbon dioxide and other similar components.

WHAT IS THE ORIGIN OF COAL AND COAL BED GAS?

Beginning with its deposition on the earth's surface and continuing throughout its history, coal undergoes a pro-progressive evolution in composition and structure termed "coalification". Coal "rank" provides a measure of the degree of coalification. The physical and chemical changes associated with coalification largely represent the response of sedimentary organic matter to elevated temperatures and pressures in the depths of the earth. Even though the composition and structure of coal may be radically altered during this process, the single term "coal" encompasses all such materials.

Rank provides the principal basis of the ASTM coal classification system used in the United States and Canada (ASTM, 1991, D-388). The ASTM rank classes begin with lignite and continues with subbituminous, bituminous, semianthracite, anthracite, and meta-anthracite. Coal in the San Juan basin increase in rank from high volatile C bituminous in the southern part of the basin to low volatile bituminous near the northern part of the basin. Although these strata were deposited at nearly the same time geologically, their rank has been increased to varying levels, reflecting differences in their coalification history.

The concept of coal rank is particularly important to coal bed gas reservoirs, as methane and other light hydrocarbons are formed from the coal itself, as by-products of coalification. Also, rank influences the capacity of coal to incorporate methane into its structure.

Chemistry of Coalification. The organic structure of coal are comprised primarily of the elements carbon, hy-

drogen, and oxygen, which are present in a diverse number of molecular structures. The process of coalification is manifested by the progressive enrichment in elemental carbon accompanied by the depletion in hydrogen and oxygen. The theoretical end member of coalification is pure carbon, in the form of graphite (Fig. 9).

To understand the chemistry of coalification, the key question is, "How and in what form are hydrogen and oxygen removed from the coal? The answer is that by-product substances are formed that are rich in hydrogen relative to carbon and oxygen relative to carbon. Examples include (CH_4, with a hydrogen to carbon ratio of 4:1) and carbon dioxide (CO_2, with an oxygen to carbon ratio of (2:1) among many others. For each one of these molecules formed and released, the residual coal becomes enriched in carbon.

For many decades it has been widely recognized that methane is one of principal by-products formed during coalification. More recently, it has been widely recognized that a whole host of other hydrocarbon by-products are formed as well, and that these are completely or partly retained within the coal structure (Lewan, in press).

It is possible to represent the overall process in a simplified fashion as follows:

[By-product Chart Omitted]

The elimination of by products is termed "devolatilization". The composition of these by-products changes with rank. Elimination of water is dominant at low ranks, carbon dioxide at intermediate ranks, and hydrocarbons at higher ranks.

Although devolatilization can successfully account for the changing elemental composition of coal (or coal macerals), it does not represent the overall process of coalification in that it fails to describe the evolution of

the coal molecular structure, particularly with regard to the formation, entrapment, and subsequent destruction of the molecular fraction of coal. The diagram in Figure 10 better describes the overall process. Here the overall composition of the coal is represented by the inner box. Coal composition is subdivided into three classes: mineral constituents, macromolecular matrix, and entrapped molecular constituents, as discussed previously. Processes occurring during coalification are represented by the arrows. These are three main types of coalification reactions, two that are degradative, and one that is constructive: 1) "depolymerization" reactions wherein the macromolecular matrix is broken up into progressively a progressively greater number of pieces, 2) "cracking", wherein the entrapped molecular fraction is broken up into progressively smaller pieces, and 3) polymerization/condensation, wherein components become covalently bonded to form a higher molecular weight product (even though a polymer in the strict sense is not formed). This process is accompanied by the formation of a smaller molecules as a by-product. All three types of the reactions produce smaller molecules as by-products. These by-products are partly retained within the coal and partly released from the coal into the surrounding strata.

The important significance of this scheme to coal bed reservoirs is that the molecular fraction of coal evolves simultaneously with the rest of the coal as part of the overall coalification process. Carbon dioxide, methane and higher hydrocarbons, water, and oil are all formed from the coal itself during coalification. In this manner, coal bed reservoirs serve as their own "source rock"; that is, the hydrocarbons contained within the coal originated within the coal.

As a consequence of processes occurring during coalification, the composition and concentration of the molecular fraction of coal is not static, but changes markedly (Fig. 2). At low rank, water is the principal molecular con-

stituent of coal comprising over 75% of peats, but decreasing to 15-20%. At medium ranks, pyridine-extractable constituents are dominant, including a diverse suite of hydrocarbons and asphaltic materials, including methane. At high rank (from medium volatile bituminous and beyond) repolymerization and cracking produce an overall decrease in the molecular fraction, although methane remains an important constituent.

Fig. 9—Van Krevelen diagram, plotting hydrogen to carbon atomic ratios on the vertical axis and oxygen to carbon atomic ratios on the horizontal axis. Analyses for coals from the San Juan basin are plotted in the crosshatched area. [Diagram omitted.]

Fig. 10—Flow chart depicting the chemical and physical processes occurring during coalification. [Chart omitted.]

WHAT ARE SOME OF THE FUNDAMENTAL DIFFERENCES BETWEEN COAL BED RESERVOIRS AND CONVENTIONAL RESERVOIRS?

The characteristics of coal as a gas "reservoir" differs from conventional hydrocarbon reservoirs in several important respects. Most of these differences have been highlighted in the previous sections, but are briefly reviewed in the following paragraphs as well.

Source Rock/Reservoir Rock Relationship. In the broadest sense, the development of any economic oil and/or gas deposit requires the more-or-less simultaneous evolution of: 1) a source rock stratum from which petroleum is generated, and 2) a reservoir stratum in which petroleum can accumulate and from which it can be profitably extracted. Typically, a stratum having good source rock properties constitutes a poor reservoir, whereas a good reservoir stratum tends to be a poor source rock. In contrast with conventional reservoir systems, however, coal can at the same time serve as both an excellent source and reservoir. Most conventional oil and gas

accumulations are "sourced" by shale beds containing "dispersed" sedimentary organic matter. Typically, the organic matter (OM) concentration in these rocks constitutes only a few weight percent. Coal beds, on the other hand, represent exceptionally thick, rich concentrations of organic source material, attaining a thickness up to tens of meters. As a consequence of the large amounts of OM contained within them, coal beds produce large quantities of hydrocarbon by-products during coalification. A proportion of the hydrocarbons so generated is retained within the coal itself, owing to the high capacity of coal to incorporate oils and gases as an inherent part of its structure. Thus the coal serves as its own source rock.

Trapping Mechanism. In conventional reservoir rocks, hydrocarbon storage capacity is provided in the form of open pores, whose sizes are typically on the order of micrometers to millimeters in dimension and which constitute perhaps 5-20% of the rock by volume. Although coal contains some pores in this size range, the porosity of typical coal bed gas reservoirs is very low—usually less than 5% and sometimes less than 1%[7]; and this porosity is typically occupied by water *in situ*. Most of the requisite "accessibility" to hydrocarbon storage is related to the "open" molecular structure of coal, which provides nanometer-scale interstices in which small molecules can reside. Of particular interest in this regard is methane which, owing to its small size, non-polar character, and low polarizability is relatively free to enter and exit the structure. This capability of coals to accommo-

[7] "Porosity" is difficult to define in the case of coal, where it represents a more-or-less integral part of the coal structure. Typically, porosity is taken to represent the proportion of the coal volume which may be occupied by a penetrating fluid, assuming that the volume of the pores and/or the fluid does not change during the measurement process. No matter how it is defined, however, it is clearly a "different sort of animal" as compared with porosity in conventional reservoir rocks.

date methane into their structure, due in part to the weak, but significant, attractive forces between methane and other coal constituents (primarily by Van der Waals' bonding), gives rise to tremendously high concentrations of methane in coal at moderate reservoir pressures. 'Equivalent' methane porosities (i.e., the imaginary volume that would be occupied by the methane if it were a free gas) can approach 100% for some coals (depending on pressure)! Once again, however, methane sorption capacity is related to the degree of coalification.

Relationship to Water. There is still "lots of room" for methane within in coal structure, even in water-saturated coals. In conventional reservoirs, if there's water in the pores, then there's no gas. Thus, when gas wells in the Ignacio anticline, underlying the Southern Ute Indian reservation "watered out" during the 1960's and 1970's, the operators assumed incorrectly that there was no more gas to be produced.

Likewise, most coal beds are initially saturated with water; and the water must be removed to initiate desorption and gas flow.

Size of Porosity. Petroleum in conventional reservoirs is entrapped in pores of various types that are typically on the order of millimeters in dimension. In contrast, the intramolecular free volume into which sorbates reside in coal are interpreted to be barely larger than the sorbate molecules themselves. To provide a concept of scale: A single methane molecule residing in a 1 millimeter-diameter pore has the same "aspect ratio" as a pin *point* (not a pin head) in a football field; whereas the microporosity in coal is barely larger than the sorbate molecules that reside within it.

Physical State of the "Gas". For the most part, the substances produced as natural gases from coal beds do not occur as free gases in the reservoir, but as occluded, sorbed species, that are much more highly concentrated

at a given pressure than they would be if in a gaseous state.

"Chromatographic Effect". In conventional reservoirs, natural gas occurs for the most part in a gaseous state. Normally, this gas comprises a blend of species which flows through the reservoir as a homogeneous mixture. In coal bed reservoirs, small molecules must diffuse through a tortuous network of organic molecules before entering the fracture network. This process allows for compositional fractionation of gases. Typically methane is the first and fastest to be released, followed by other constituents. This "chromatographic effect" (Wyman, 1984) provides evidence for the intramolecular storage mechanism of the methane, etc.

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